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THE ORIGIN OF THE TUNGSTEN ORES OF BOULDER COUNTY, COLORADO.[1]

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ABSTRACT.

A narrow zone of sericitic alteration encases the Boulder County ferberite veins, but gives way abruptly to a wide outer envelope of argillized rock. The mineralogy indicates sustained attack by early acid solutions that finally changed to neutral and alkaline solutions. Sericitic alteration is conspicuous next to the gold telluride veins and the argillic envelope is rare. The mineralogy of the tungsten and telluride vein filling indicates a progressive change from acid to alkaline solutions and harmonizes with the evidence given by the wall rock alteration. Experiments and the paragenesis suggest that ferberite was precipitated in slightly acid solutions. Galena, tetrahedrite and the gold tellurides are later and presumably precipitated in alkaline solutions. Relatively late pre-ore dikes of biotite latite and latitic explosion breccia are associated with the tungsten and gold-telluride veins. Their composition and field relations suggest that a biotite latite magma heavily charged with volatiles was the source of the mineralizing solutions. It is believed that acid emanations from this magma rose through hot porous explosion breccia with little change in character, but soon dropped their load above the upward termination of the breccia in the overlying fissures where they reacted with the wall rock and became neutralized and finally alkaline through the acquisition of bases from the quartz monzonite that makes up the country rock of the deposit.

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INTRODUCTION.

Location and Production.—The Boulder County tungsten district is close to the eastern edge of the Front Range just west of Boulder, Colorado (Fig. 1). The tungsten deposits extend in a

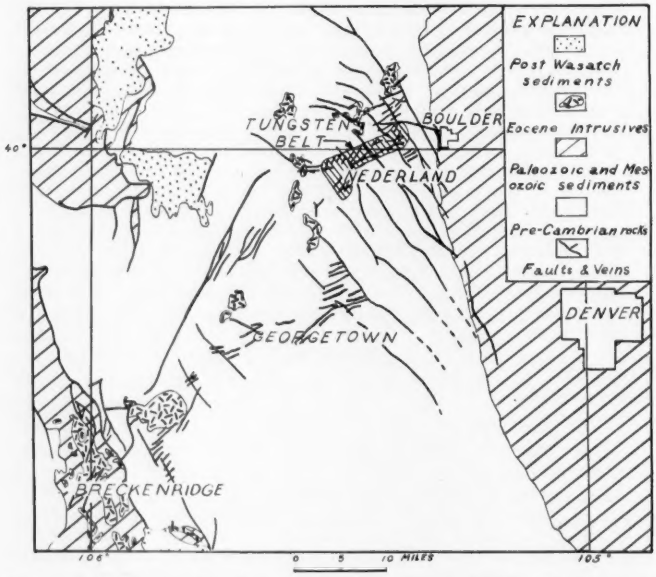

FIG. 1. Index map showing the location of the Boulder County tungsten belt and the general features of the regional geology.

narrow belt from Arkansas Mountain, 9½ miles W–SW to Sherwood Flats, 1½ miles northwest of Nederland.

Tungsten ore was first recognized in the district by H. H. Wanamaker in 1900, and from that year to the present the district has been continuously productive with the exception of the years 1921, 1922, and 1932. The total production from 1900 through 1937 is approximately 20,350 tons of tungsten concentrate (60 per cent WO_3), a total production more than 50 per cent greater than that of any other tungsten district in the United States; since 1918, however, the annual production has only averaged about 200 tons of concentrate.

Acknowledgments.—In 1930 the U. S. Geological Survey in cooperation with the State of Colorado and the Colorado Metal Mining Fund began a study of the Boulder County tungsten district, of which the final report is in preparation. The writer was assisted in the field work in different years by E. B. Eckel, James Boyd, Vernon Scheid, Ogden Tweto, and Lanphere Graff. R. M. Rigg[2] made a petrographic study of the writer's thin sections of the altered wall rock of the tungsten veins and recognized the effects of beidellitic and sericitic types of alteration. This work suggested the desirability of the present more detailed study in which C. S. Ross has assisted greatly in the identification of the various clay minerals. It is doubtful if the study of the wall-rock alteration could have been satisfactorily done without the benefit of his extensive experience with this difficult family of minerals.

The district was first studied by George and Crawford[3] during 1907 and 1908, but the unusual character of the wall-rock alteration and its bearing on the genesis of the deposits was not recognized by them or subsequent investigators, although Loomis[4]

[2] Rigg, R. M.: Mineralization and rock alteration in the Nederland district, Colorado. University of Michigan thesis, 1937.

[3] George, R. D.: The main tungsten area of Boulder County, Colorado, with notes on the intrusive rocks by R. D. Crawford. Colo. Geol. Surv., First Report, 1908: 13–103, 1909.

[4] Loomis, F. B., Jr.: Boulder County tungsten ores. ECON. GEOL., 32: 952–963, 1937.

notes that fragments included in the veins contain minerals of the montmorillonite-beidellite-nontronite series.

GENERAL GEOLOGY.

Approximately three-fourths of the district lies within a small batholith of gneissic pre-Cambrian quartz monzonite, known as the Boulder Creek granite, which extends westward from Boulder to within a mile of Nederland. A productive portion of the district lies within the area of metamorphic rocks bordering the batholith on the west. Here quartz-biotite schist of the early pre-Cambrian Idaho Springs formation has been intimately intruded by small bodies of aplite and pegmatite related to the monzonite. These small intrusive bodies are irregular in outline but in general their long dimensions trend north-northwest, parallel to the schistosity of the Idaho Springs formation and its contact with the batholith. Dikes of hornblende monzonite porphyry of Laramide age are common in the western half of the district. Early Tertiary biotite monzonite porphyry dikes with an associated biotite latite intrusion breccia are found in several localities in the eastern part of the district, and are believed to represent the source magma from which the tungsten ores were derived. Aside from some small disseminated deposits in the western part of the district, all of the tungsten ore occurs in veins as fissure filling. Some of the veins are persistent branching fissures that can be followed for more than a mile, but others can be followed for only a hundred yards or less. A few of the important veins near the western limit of tungsten mineralization strike N–NW, but most of the ore is in veins that strike E–NE. The veins follow steeply-dipping, pre-mineral faults of small displacement, and with a relatively large horizontal component of movement. The repeated brecciation of the vein filling shows that movement preceded, accompanied, and followed the period of tungsten metallization.

The production of the district has come from many small shallow ore shoots, few of which persisted to a depth of more than 200 feet. A little ore was found as deep as 600 feet below

the surface in the Conger mine, but in only two other mines in the district, the Clyde and the Coldspring, has ore been found to as great a depth as 500 feet.

An inner zone with sericite and an outer zone with clay minerals mark nearly all of the larger veins of the district. Strong alteration generally extends through a distance 5 to 20 times the width of the vein itself.

The vein filling is made up of many generations of finely crystalline quartz and fine to medium-grained ferberite, with minor amounts of other minerals. The ore mined contains from 1½ to 20 per cent WO_3. Commonly the ferberite forms the matrix of a breccia of country rock and early vein quartz, and locally grades into seams of nearly pure massive ore a few inches wide (Fig. 2). Less often brecciated masses of ferberite are found

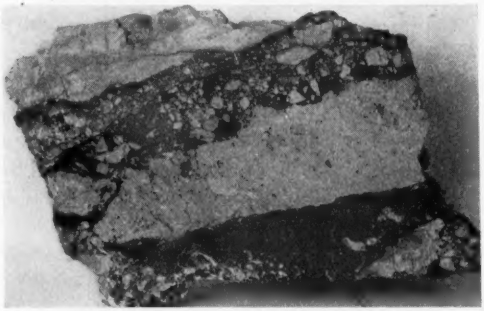

FIG. 2. Polished section of typical ore from Coldspring mine. ×3/5. Ferberite-bearing quartz black; barren horn quartz and brecciated granite light gray.

cemented by later quartz. Drusy openings are common and the district is famous for its beautiful specimens of sparkling black euhedral ferberite crystals that line open spaces in many of the veins. The different types of ore are especially well illustrated in a paper by Hess and Schaller,[5] which gives a good account of the mineralogy and crystallography of the ores. The relations

[5] Hess, F. L., and Schaller, W. T.: Colorado ferberite and the wolframite series. U. S. Geol. Surv. Bull. 583, 1914.

of the ore to the minor amounts of hematite, magnetite, fluorite, dickite, ankerite, siderite, marcasite, pyrite, barite, calcite, galena, sphalerite, freibergite, tetrahedrite, miargyrite, adularia, opal, montmorillonite, halloysite, and beidellite, with which it is associated in places, is considered in the discussion of the vein filling.

The tungsten deposits are later than dikes of early Tertiary age and earlier than the oldest erosion surfaces recognized in this part of the Front Range. The mineral composition is typical of epithermal veins and the association of the tungsten deposits with other ore deposits of the mineral belt leads to the belief that they were formed during one of the later stages of the Laramide Revolution early in the Tertiary period.

Some features of the tungsten deposits are unusual and it is believed a summary of the evidence concerning the origin of the ores may be of interest in advance of the report that is to be published by the Geological Survey. The simple but genetically significant mineral composition of the vein filling and altered wall rock indicates solutions that were first acid, then neutral, and finally alkaline. The evidence allows a fairly definite picture to be drawn of the successive changes undergone by the mineralizing solutions and of the chemistry of ore deposition in the district.

WALL-ROCK ALTERATION.

Mineralogy.—One of the most striking features of the district is the almost universal presence of two sharp divisions in the envelope of altered rock adjacent to the veins. As a vein is approached, the country rock becomes bleached and soft, but adjacent to the vein its appearance changes remarkably. The bleached, chalky aspect is lost, giving way abruptly to rock of much more normal appearance (Fig. 3). The general effect is that of a layer of fresh granite separating the vein from a wide zone of strongly altered granite, which in turn grades outward gradually into fresh rock. Under the microscope the apparently fresh rock close to the vein is found to be strongly sericitized, slightly silicified, and to contain some carbonate. The bleached zone outside the sericitized rock contains many different clay minerals and relatively little sericite. Wall rocks along nearly

FIG. 3. Sericitized casing of the Coldspring Vein, No. 5 level, showing contact with vein at pick point and abrupt change into the argillized envelope near end of handle.

all the veins in the district show the two sharp divisions whether the veins are large or small, barren or productive; however, a few locally productive veins lie in almost unaltered rock.

The unaltered country rock of most of the deposits is a fairly uniform dark gray, gneissic, coarse-grained, slightly porphyritic biotite-quartz monzonite that shows well defined platy and linear structure. Near the margins of the batholith this rock is somewhat more gneissic and less evenly grained, and contains more biotite than elsewhere. In most places it consists essentially of quartz, orthoclase, microcline, oligoclase, and biotite. Locally it is somewhat more calcic and may contain hornblende, and here the plagioclase is commonly andesine rather than oligoclase. Ferromagnesian minerals make up from 10 to 20 per cent of the rock, plagioclase from 20 to 30 per cent, orthoclase and microcline from 20 to 30 per cent, and quartz from 15 to 30 per cent. Ilmenite and apatite are abundant accessory minerals.

In the argillized [5a] zone the minerals of the quartz monzonite are selectively attacked. Quartz and orthoclase are stable except in the area of most intense alteration where they may be slightly replaced by dickite. Biotite is relatively stable but breaks down where the alteration is severe. Oligoclase and andesine are the most susceptible of the minerals and in many places have been completely argillized although the associated biotite is nearly fresh. Apatite is stable throughout the zone of alteration, but ilmenite is not.

The argillized envelope may be divided into three sub-zones: (1) An outer sub-zone where the bleached rock grades into the fresh, and in which the chief alteration minerals are allophane, montmorillonite (?), hydrous mica, and sericite; (2) A transition sub-zone in which beidellite is abundant; (3) An inner sub-zone of intense alteration containing much dickite. The transition from the dickite sub-zone to the fresher appearing sericitized rock that forms the casing about the vein is abrupt, but, although the contact may appear to be of knife-edge sharpness megascopically, thin sections show some dickite and beidellite within the sericitized casing.

In the outermost sub-zone of alteration the plagioclase is replaced along crystallographic directions by sericite and nearly amorphous clay. The refractive index of the clay is close to 1.48 and much of it is isotropic, but some has a low birefringence. It is believed to be a mixture of amorphous allophane and a crystalline clay mineral of very low birefringence related to montmorillonite. This mixture will be designated allophane-clay. It is disseminated in very fine blebs and shreds through irregular areas of the plagioclase. The sericite, in contrast, cuts sharply through these areas in well-oriented stringers parallel, or, to a less extent, nearly perpendicular to the twinning lamellae of the

[5a] The terms "argillic," "argillized," "argilliferous," formed from the root word argil, meaning a white clay, are used here to describe the effects of hydrothermal alteration that has resulted in the prominent development of clay minerals. Most mineralogic terms such as "kaolinic," imply the presence of specific minerals, and are both inappropriate and misleading if the minerals suggested are not present. The term "argillic" seems free from this criticism.

oligoclase. The allophane-clay is the most wide-spread of the clay materials and is found throughout the altered wall rock whether the alteration is of the sericitic or argillic type. It is also very common in the vein filling, especially where there is an abundance of the late clay minerals that formed after the deposition of ferberite ceased. In this outermost sub-zone both sphene and ilmenite are slightly altered to leucoxene, but the other minerals of the gneiss are fresh.

Closer to the vein, where the plagioclase crystals of the rocks are visibly bleached, beidellite is present and reaches its maximum development approximately where dickite first appears. It is distinctly earlier than dickite and commonly forms a selvage along the edges of replacement veinlets of dickite. The replacement veinlets interlace in the oligoclase with no regard for crystallographic direction, in contrast to the definite pattern of replacement shown by allophane-clay and sericite in the outer subzone (Fig. 4). The oligoclase alters directly to dickite and beidellite where it has not already been sericitized or replaced by allophane-clay, and in such places the beidellite replaces allophane-clay extensively but leaves sericite little attacked. The replacement veinlets that show a central seam of dickite and an outer border of beidellite continue into strongly sericitized areas with much diminished vigor, and only the dickite portion cuts through the sericite. This relation suggests a reaction coating or buffer fringe of beidellite between the dickite and oligoclase and a two-step reaction in the conversion of the plagioclase to dickite along the middles of the veinlets. The formation of beidellite was not confined to borders of dickite veinlets, however, and much of the plagioclase is changed to beidellite with no development of dickite. This beidellite is generally intergrown with another clay mineral that is provisionally called hydrous mica. Hydrous mica has a refractive index slightly less than that of sericite but greater than that of dickite, and its birefringence is nearly the same as that of beidellite. Its appearance and optical character are identical with a muscovite-like mineral described by Ross and Kerr [6] and its

[6] Ross, C. S., and Kerr, P. F.: The kaolin minerals. U. S. Geol. Surv. Prof. Pap. 165: 172, 1931.

refractive indices are lower than those of illite.[7] The beidellite-hydrous mica intergrowth occupies irregular areas of alteration in the oligoclase and appears as fine-grained masses that are hard to distinguish from those of sericite. These areas are confined to oligoclase and shun microcline and orthoclase as well as sericite and biotite. In some of the beidellite-hydrous mica masses, irregular areas seem to be partly altered to nearly isotropic amorphous material in which dickite crystals have formed. As the refractive index of this isotropic alteration product is close to 1.54, it is probably halloysite. The dickite seems to have developed through a gradual molecular readjustment of the halloysite, which in turn must have formed from the reaction between beidellite-hydrous mica masses and solutions with which they were not in equilibrium (Figs. 5, 6). Coarse-grained, well-crystallized dickite is found in veins that cut sharply across the other clay minerals. In the beidellite sub-zone some of the biotite shows slight decolorization and contains finger-like seams of siderite and leucoxene. The accessory sphene is almost completely converted into leucoxene, and the ilmenite shows incipient alteration to hematite by the presence of a few tiny veinlets of this mineral in many of the crystals. Nearly all are bordered by a halo of leucoxene.

Between the beidellite sub-zone and the sericitized casing, the rock contains a larger amount of dickite than it does farther from the vein, but the general relations described above hold within the sub-zone where dickite is the dominant clay mineral. Some of the orthoclase and microcline grains show a slight development of oriented allophane-clay blebs, and a few are veined with beidellite or dickite. Much of the biotite also appears fresh, though as a whole it is more altered than in the beidellite sub-zone. Some of the bleached stringers of biotite are probably close to amesite or antigorite in composition, but the typical green chlorites of low birefringence are conspicuously absent. Beidellite or dickite have partly replaced some biotite crystals, but the most abundant

[7] Grim, R. E., Bray, R. H., and Bradley, W. F.: The mica in argillaceous sediments. Am. Min., *22*: 818, 1937.

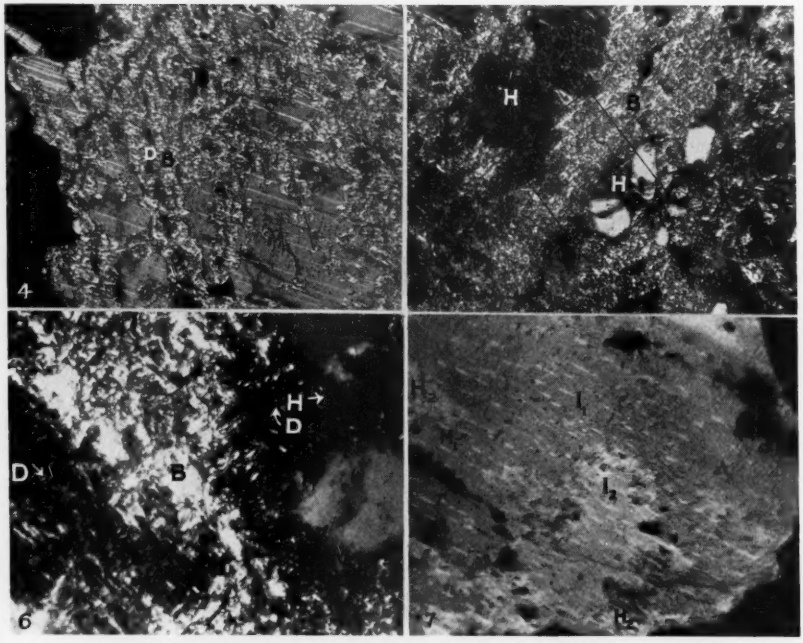

FIG. 4. Boulder Creek granite, 10 feet from Coldspring Vein. Beidellite (B) and dickite (D) replacing oligoclase in interlacing veinlets. X-nicols, × 70.

FIG. 5. Boulder Creek granite 3 feet from Coldspring vein. Beidellite (B) partly altered to halloysite (H) in which dickite has grown. Area of Fig. 6 outlined. X-nicols, × 100.

FIG. 6. Portion of halloysite area of Fig. 5, showing development of dickite (D) in the isotropic halloysite (H). X-nicols, × 355.

FIG. 7. Polished section of Boulder Creek granite from 4 level of Conger mine, 18 feet east of Conger vein. Ilmenite (I_1) with primary exsolved hematite rods (H_1) partly altered to a later violet-colored ilmenite (I_2) with some late hematite (H_2) near edge of crystal. × 430.

alteration products in biotite are late siderite and leucoxene seams, quartz veinlets following the cleavage, and the decolorized areas of amesite (?). In the dickite subzone sphene has not been observed except in the form of the abundant leucoxene which occurs in veinlets cutting across the other minerals and in girdles and veinlets developed by the alteration of ilmenite and biotite. The ilmenite itself in this subzone has been completely replaced by hematite and leucoxene—a mineralogic shift of considerable genetic significance (Fig. 7).

Close to the vein the argillic envelope gives way abruptly to the sericitic casing. The sericitized zone ranges in width from less than an inch along small veins to a maximum of about three feet along the largest veins of the district. In it beidellite is lacking but fine-grained hydrous mica is abundant and is closely associated with dickite. In many places it is evident that coarse-grained hydrous mica has grown at the expense of dickite, and it is believed that the abundant hydrous mica in the fine-grained intergrowths with dickite probably has had a similar origin. Coarse-grained sericite is intergrown with the coarsest-grained of the hydrous mica and may be contemporaneous with it; however, veinlets of fine-grained quartz and coarse-grained sericite cut and replace the fine-grained hydrous mica-dickite masses (Figs. 8, 9). Veinlets of adularia are locally abundant and later than the quartz-sericite veinlets. Although much of the quartz is nearly contemporaneous with the coarse-grained sericite some of it is free from sericite and probably somewhat later. In this zone or casing secondary sphene is fairly common locally and is a late mineral, generally associated with veinlets of carbonate. The ilmenite of the rock which had been converted to hematite in the dickite subzone is changed to magnetite or pyrite in the quartz-sericite casing.

The biotite in the rock close to the vein is in large part altered to fine-grained dickite, which in turn is strongly replaced by coarse-grained sericite and to a less extent by veinlets of carbonate, secondary sphene, and quartz. Orthoclase, microcline, quartz, and apatite show very little replacement.

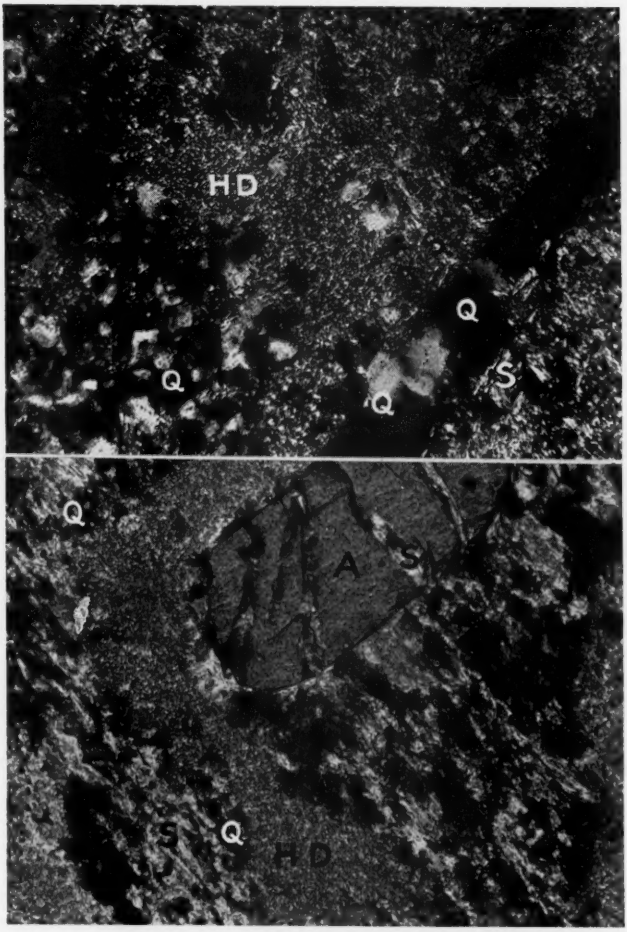

FIG. 8 (Upper). Sericitized Boulder Creek granite next to the Coldspring vein, 5 level. Quartz (Q) cuts and replaces fine-grained hydrous mica-dickite mass (HD) and medium-grained sericite (S). X-nicols, × 145.

FIG. 9 (Lower). Sericitized Boulder Creek granite next to the Coldspring vein, 5 level. Quartz (Q) and coarse-grained sericite (S) cut apatite (A) and replace hydrous mica-dickite area (HD). X-nicols, × 100.

Chemical Changes.—As shown in Table 1 and Figs. 10 and 11, analyses of specimens ranging from fresh to thoroughly altered rock show a consistent progressive change from the outermost zone to the edge of the sericitized casing, where a sharp reversal in the chemical trend takes place.

TABLE 1.

ALTERED WALL ROCKS, BOULDER COUNTY TUNGSTEN DISTRICT, COLORADO.
J. G. Fairchild, Analyst.

No. of sample	1	2	3	4	5	6
	Fresh	Alt.	Alt.	Alt.	Fresh	Alt.
SiO_2	68.71	66.61	63.34	65.67	66.31	65.08
Al_2O_3	14.93	15.13	18.21	16.52	15.07	15.26
Fe_2O_3	1.02	1.40	0.79	1.21	1.35	1.30
FeO	2.07	2.26	2.44	2.53	2.71	2.90
MgO	1.50	1.45	1.08	1.00	1.03	0.93
CaO	2.01	1.23	0.40	0.08	2.06	0.43
Na_2O	2.85	1.20	0.41	0.81	2.48	0.94
K_2O	5.14	5.02	6.11	6.70	5.96	8.63
H_2O^-	0.14	1.45	0.71	0.94	0.06	0.17
H_2O^+	0.56	2.08	4.07	2.34	0.90	1.38
TiO_2	0.62	0.54	0.75	0.33	0.66	0.75
CO_2	0.46	1.09	1.16	1.70	0.98	1.75
P_2O_5	0.16	1.19	0.24	0.22	0.32	0.31
SO_3	....	....	....	....	....	0.64
S (total)	trace?	0.02	0.04	0.02	0.04	....
	100.17	99.67	99.75	100.07	99.93	100.47
Powder density	2.671	2.625	2.642	2.673	2.700	2.688
Bulk density	2.631	2.173	2.177	2.283	2.710	2.461

Nos. 1, 2, 3 and 4 are samples of Boulder Creek granite from the 5 Level of the Coldspring mine collected at distances of 35 ft., 10 ft., 3 ft., and ½ inch from a well mineralized portion of the vein.

No. 5 is fresh aplite of the Boulder Creek granite six feet from a barren portion of the Rakeoff vein in the Lily adit.

No. 6 is altered aplite adjacent to the Rakeoff vein, Lily adit.

A plot of the molecular percentages of the constituents contained in the same volume of rock shows a continual decrease in the proportion of silica through the argillized rock and an abrupt increase in the silicified zone next to the vein (Figs. 10, 11). The alumina and total iron remain nearly constant but the proportion of ferrous oxide to ferric oxide has a maximum in the dickite sub-zone. Magnesium oxide and calcium oxide decrease

through both zones. Potash decreases in the outer sub-zone of argillization and increases through the more intense area of alteration, both in the dickite sub-zone and in the sericite casing. Soda decreases sharply throughout the zone of argillization and increases slightly in the zone of sericitization. Carbon dioxide, as would be expected, increases but slightly through the zone of argillization and shows a marked increase in the zone of seri-

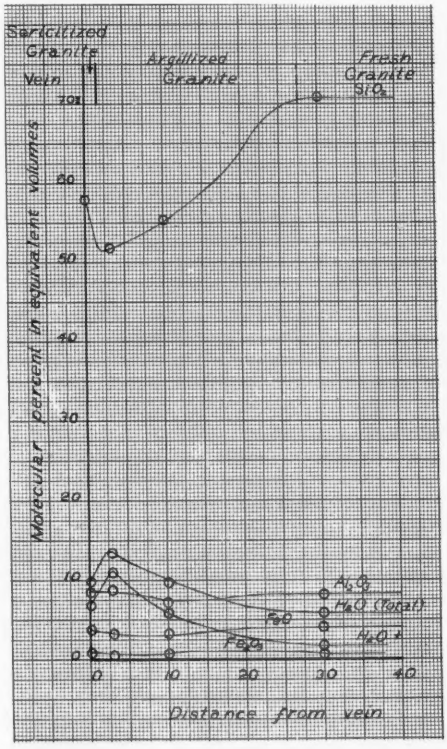

FIG. 10. Changes in molecular proportion of SiO_2, H_2O, Al_2O_3, FeO, and Fe_2O_3 in equivalent volumes of altered Boulder Creek granite adjacent to vein, 5 level, Coldspring mine.

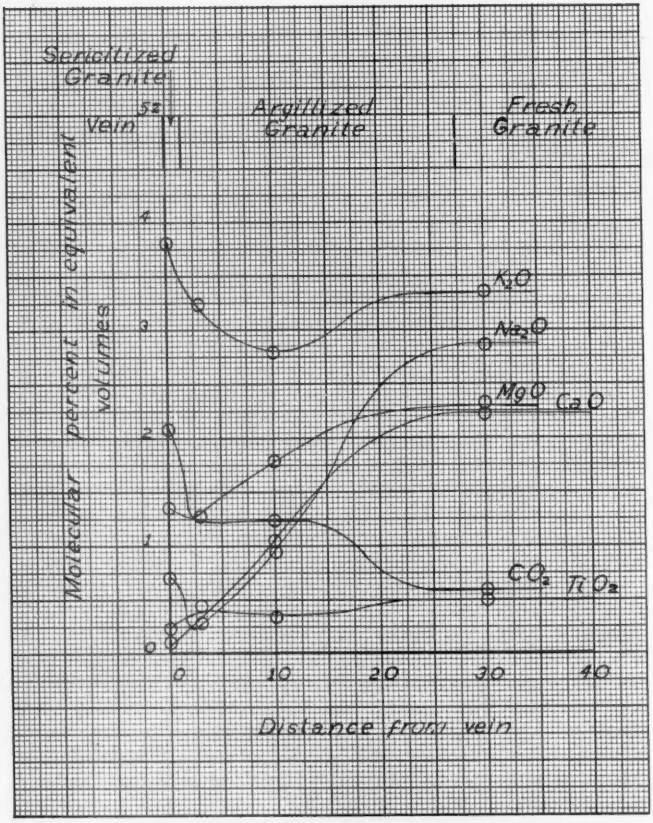

FIG. 11. Changes in molecular proportion of MgO, CaO, Na_2O, K_2O, and CO_2 in equivalent volumes of altered rock adjacent to Coldspring vein.

citization. Total water reaches its maximum just outside the sericite casing, and where dickite is most abundant the water driven off above 100° is much in excess of water lost below this temperature. Farther away from the vein, where beidellite is important, the H_2O+ diminishes in amount and the H_2O-

increases in harmony with the dehydration curves of the two clays.

The inflection points of most of the curves shown in Figs. 10 and 11, where the sericitic gives way to the argillic alteration, are striking and quite unlike graphs that represent alteration in most mining districts. The paragenesis of the alteration minerals and the chemical changes in the wall rock indicate that sericitic alteration was superposed on an earlier argillic type, and suggest a radical change in the nature of the altering solutions at a late stage in the period of mineralization.

Character of the Solutions Causing the Alteration.—In their study of the hot springs of Lassen Peak, Day and Allen [8] state that the kaolin minerals are the product of hot or cold acid waters in contrast to sericite which presumably formed from alkaline solutions. With this statement Lindgren [9] expressed his complete agreement. This view received strong support from the experimental work of Noll,[10] who synthesized the clay minerals in alkaline and acid solutions. He found that the formation of montmorillonite (a clay mineral almost identical with beidellite) depends on the cation concentration and that this clay mineral, in contrast to "kaolin" (kaolinite?), forms best in solutions of definitely alkaline character. Kaolin formed instead of montmorillonite in solutions of bicarbonates, chlorides, and sulphates, especially if they were acid. Active circulation of dilute solutions and the presence of carbonic acid or hydrochloric acid caused kaolin to form. The converse of these conditions resulted in montmorillonite. As the potash concentration increased, sericite formed instead of montmorillonite and was the usual end product of solutions of potassium hydroxide. Although the stability ranges of these minerals overlapped, the generalization seemed warranted that kaolin minerals reflected an acid solution, mont-

[8] Day, A. L., and Allen, E. T.: Volcanic activity and hot springs of Lassen Peak. Carnegie Inst., Publ. 360: 141, 1925.

[9] Lindgren, Waldemar: Mineral Deposits, McGraw-Hill, p. 457, 1933.

[10] Noll, W.: Synthese von Montmorilloniten. Chemie der Eerde, 10: 129–153, Gustav Fischer, Jena, 1936.

morillonite a neutral or slightly alkaline solution, and sericite a more strongly alkaline solution, rich in potash.

The behavior of iron in the oxidized zone of ore deposits as well as the chemistry of the element as we know it in the laboratory indicates that oxidation from the ferrous to the ferric state is characteristic of acid solutions or neutral ones carrying free oxygen. Only free oxygen and a very few powerful and unusual oxidizing agents are known to be capable of oxidizing ferrous to ferric iron in alkaline solution, and it is unlikely that such solutions exist in nature. Gruner [11] reported that, with constant displacement of equilibria, it is possible to show appreciable oxidation of ferrous iron at elevated temperatures by the use of only steam. However, the effectiveness of this reagent was very small as compared with that of steam to which a minute amount of hydrochloric acid had been added.

More recently Linder and Gruner [12] reported the production of hematite through the action of sodium sulphide solution on fayalite (Fe_2SiO_4) and magnetite, and suggested that this alkaline solution was in part an oxidizing agent at high temperatures. According to the description of the products of reaction with fayalite, most of the material formed was acmite and ferrous sulphide, but some small crystals of hematite were intergrown with the acmite. Reaction between sodium sulphide and ferrous silicate, however, would be expected to produce ferrous sulphide and sodium silicate; therefore, the few small crystals of hematite seem incongruous and suggest that the oxidizing agent must be sought elsewhere, presumably in some contaminant such as air. The fact that free sulphur formed during the attack of sodium sulphide solutions on orthoclase definitely shows that oxidation took place, as the authors point out, but surely no oxidizing agent exists in orthoclase, and the presence of a contaminant such as air seems clearly indicated. The only experiment noted in which hematite formed abundantly was one involving the derivation of

[11] Gruner, J. W.: Hydrothermal oxidation and leaching experiments. Econ. Geol., 25: 704–715, 1930.

[12] Linder, J. L., and Gruner, J. W.: Action of alkali sulphide solutions on minerals at elevated temperatures. Econ. Geol., 34: 537–560, 1939.

hematite from magnetite. In this experiment, however, ferrous sulphide, as well as hematite, was a reaction product. No iron was oxidized; instead, the ferrous oxide in magnetite was converted to ferrous sulphide by reaction with sodium sulphide and water, according to the following equation:

$$Fe_2O_3 . FeO + Na_2S + H_2O \rightleftharpoons Fe_2O_3 + FeS + 2NaOH.$$

It would thus seem that these experiments, far from proving that ferrous iron can be oxidized in alkaline *oxygen-free* solutions, suggest that the presence of free oxygen is essential to produce oxidation in other than acid solutions.

Although free oxygen is a common constituent of fumarolic gases, its association with nitrogen in about the proportion of 1 to 4 has led investigators to ascribe it to contamination with air or meteoric waters.[13] The possibility that the solutions that altered ilmenite to hematite in the dickite sub-zone were alkaline or neutral oxygen-rich hypogene solutions seems less likely than that the oxidation from ferrous to ferric iron took place in hot acid solutions, which were also instrumental in altering oligoclase and the other aluminum silicate minerals to dickite. Beidellite probably formed under nearly neutral conditions while the allophane-clay and sericite were developing in the outer fringe of permeable rock where the spent solutions had become alkaline. The presence of adularia, carbonate, sericite, magnetite, and pyrite in the narrow zone of sericitic alteration at the edge of the vein must mean a later change from acid to alkaline. The optimum development of hydrous mica in this zone indicates that its growth was furthered by neutral or alkaline solutions.

VEIN FILLING.

The veins record many changes in the mineralizing solutions, but the general sequence of deposition is consistent throughout the district. In some places a reversal from the normal order is found locally, but it is readily explainable in terms of minor

[13] Clarke, F. W.: The data of geochemistry. U. S. Geol. Surv. Bull. 770: 262–272, 1924.

changes in the routes followed by the most active mineralizing currents in the fissure. It is believed that the sequence in the tungsten veins is due to a continual process of mineralization and thus represents a single stage of magmatic activity that can be regarded as a unit.

Quartz Gangue.—The early filling of the tungsten veins was chiefly fine-grained quartz, known as "horn" or "horn quartz" by the miners. In most places other minerals are disseminated through this barren quartz in only meager amounts. Locally, fragments of pyritic vein quartz are found and quartz of this type contains a little gold. It belongs to an earlier period of mineralization, however, and its sporadic appearance in the tungsten veins is unrelated to the epoch of tungsten mineralization. This early grey pyritic horn quartz represents one of the earliest vein fillings in the district and contains no marcasite. The pyrite is mostly present in medium- to fine-grained euhedral pyritohedrons packed closely in fine-grained sericitic quartz. A little ankerite is also found that is later than the pyritic horn quartz but earlier than the white quartz that contains the disseminated clay minerals characteristic of the tungsten mineralization.

A milky white horn quartz makes up the greater part of the filling in most of the tungsten veins and is the earliest of the minerals related to the ferberite mineralization. It owes its color to a porous texture and finely disseminated clay minerals. Hydrous mica, beidellite, and dickite are found in some of the white quartz and are associated with a potash-bearing goyazite of the alunite family, but where sericite is present the clay commonly consists of allophane clay. Goyazite and fluorite may be found in and near vuggy openings within the early sericitic white quartz. Both beidellite and dickite are much less common in the vein quartz than might be expected from their abundance in the altered wall rock. It would seem that only a small amount of alumina was precipitated in any form from the mineralizing solutions, although they were instrumental in causing a vast amount of molecular rearrangement of aluminous compounds in the wall rock. A fine-grained red quartz that owes its color to disseminated hematite is

later than some of the white quartz but earlier than a grey dickite-bearing quartz, which in turn is earlier than a light green horn quartz.

An alunite-like mineral is abundantly disseminated through the barren green horn quartz and in many places is associated with ferberite. It was first identified as hamlinite by Schaller,[14] but later he pointed out its identity with goyazite and recommended the latter term as preferable.[15] The optical character of the Boulder County mineral indicates that it is very close to goyazite, the hydrous strontium aluminum phosphate, but the presence of a small amount of sulphate in the material identified by Schaller shows it to be intermediate between pure goyazite ($2SrO.3Al_2O_3.2P_2O_5.7H_2O$) and svanbergite ($2SrO.3Al_2O_3.P_2O_5.2SO_3.6H_2O$), both members of the alunite group. On the Rogers tract in Boulder County near the center of the tungsten belt, specular hematite is found with goyazite and ferberite but, according to Hess[16] the goyazite is more closely associated with hematite than it is with ferberite. This occurrence, however, is unusual and in most of the rock that contains goyazite hematite is rare. At many places in the tungsten belt goyazite is found with siderite, ferberite, or early barite, but most of it formed before these minerals were deposited.

Green horn quartz is found chiefly in the barren portions of the veins near ore shoots and the color is probably caused by the high concentration of minute crystals of sulphate-bearing goyazite. A small amount of sericite and allophane clay is also disseminated through the green quartz and an occasional tiny crystal of ferberite may be seen. Locally the green quartz is brecciated and cemented by a blue-grey horn quartz that grades into black horn and contains abundant disseminated ferberite crystals of from 1/100 to 1/10 mm. in length. As would be expected, the black

[14] Hess, F. L., and Schaller, W. T.: Colorado ferberite and the wolframite series. U. S. Geol. Surv., Bull. 583: 14.

[15] Schaller, W. T.: On the identity of hamlinite with goyazite. Amer. Jour. Sci. 43: 163–164, 1917.

[16] Hess, F. L.: Tungsten. Mineral Resources of the United States, 1917. Part I, p. 941; U. S. Geol. Surv., 1921.

horn quartz represents the early stage of the ferberite ore deposition and the precursor of the commercial metallization.

A late, fine-grained, seal-brown quartz is found at some places and at first was believed to represent supergene alteration of hypogene pyritic quartz. Further study, however, showed that it is commonly interlayered with gray pyritic quartz and that both types had been brecciated and cemented by a still later white quartz. Under the microscope extremely minute dust-like particles of iron hydroxide are seen disseminated throughout the brown quartz, which also contains a small amount of disseminated pyrite showing no signs of oxidation. Fragments of earlier marcasite-bearing quartz imbedded in the brown horn quartz show no signs of oxidation and lead to the conclusion that the brown quartz represents hypogene "limonite" disseminated through fine-grained quartz.

Tungsten Ore.—The ore comprises several generations of ferberite and ferberite-bearing quartz. Although the change from ferberite to late barren quartz may be abrupt, in many places the ore shows a smooth transition from light gray to black or black to light gray, and reflects the gradual appearance or disappearance of conditions favoring the deposition of ferberite. Under the microscope, siderite is seen to be a common associate of ferberite crystals, but it is seldom abundant enough to be recognized in the hand specimen. Wherever its relation to the ore could be ascertained, the siderite is earlier than or contemporaneous with the ferberite (Fig. 12) and is especially common in the late gray variety of horn quartz which followed the green horn and immediately preceded ore deposition. Some goyazite is closely associated with ferberite, but most of this mineral is earlier than the ore. A small amount of barite is earlier than ferberite and is found locally in the pyritic quartz that immediately preceded the ore-forming stage. It is rarely contemporaneous with the ore. Most of the barite is distinctly later than the ferberite and is commonly found in partly filled vugs above or at the sides of ore shoots, where it is accompanied by beidellite and a few small crystals of pyrite or rarely sphalerite and galena. A few specimens

of scheelite have been found but the mineral is rare, and in all occurrences is a late mineral. It is associated with late clay minerals and calcite in vugs, and it is later than any sulphide in the few places where it was found associated with them.

Sulphides.—In addition to the early pyrite, a small amount of iron sulphide is closely associated with the ferberite in several localities, but many periods of brecciation and quartz deposition intervened between the early pyritic mineralization and the precipitation of the sulphides that accompanied that of ferberite. Both pyrite and marcasite are present in the tungsten veins, but marcasite appears to be the earliest iron sulphide related to the ferebrite mineralization. It is most common in pre-ferberite quartz but is not uncommon in association with pyrite of post-ferberite age, and has been found contemporaneous with ferberite in only one specimen. It is present both as separate crystals and as intergrowths with pyrite in complex dendritic, frost-like patterns.

The iron sulphides appear first as a few scattered grains in the pre-ferberite gray horn quartz of the vein a little wallward from the ore and become more and more abundant as the ore is approached. Both marcasite and pyrite are generally present but the proportion of marcasite present becomes less and less as the ferberite-bearing layers are approached. At the same time, however, the proportion of pyrite rises and where sulphides are intergrown with abundant ferberite, marcasite is almost never found. In some places the pyrite stops abruptly at the ore band; in others it is present in the ferberite as minute cores, and in a few places it continues into the ore with no change in amount. In the early black horn quartz that contains a small amount of disseminated ferberite, marking the beginning of the ore-forming stage, the associated iron sulphide is chiefly pyrite but some pyrite crystals may show cores of marcasite. Clay is found with the iron sulphide in places. Most of that found with marcasite consists of dickite, but in a few places beidellite and allophane clay are present instead. The period of sulphide deposition outlasted that of ferberite deposition, although the total amount of iron sul-

phide formed was insignificant compared with that of ferberite. A considerable proportion of the pyrite and some of the marcasite were later than the ferberite in many of the specimens studied (Fig. 13). Almost invariably the size of the ferberite crystals increases and the amount of ferberite decreases where the associated pyrite contains intergrown marcasite. In specimens showing the later stages of ore deposition it has been noted that as the marcasite makes up an increasing per cent of the iron sulphide, the ferberite becomes sparser, and where the late pyrite-marcasite intergrowth gives way to well-formed marcasite crystals with a little pyrite, the quartz becomes barren of ferberite.

A specimen from a branch of the Clyde vein on the 200-foot level shows an interesting gradation from ferberite-bearing gray quartz to the brown horn. Some of the ferberite in the gray quartz is poikilitically enclosed by marcasite. This gray quartz grades into a band of seal-brown quartz through alternating layers of light-brown quartz, gray ferberite-bearing quartz, clear colorless quartz, gray ferberite-bearing quartz, and light-brown quartz. Here the first ferberite is associated with marcasite and the succeeding layers show less and less marcasite and an increasing amount of pyrite. In the brown horn quartz itself disseminated pyrite is present but marcasite is absent except in the fragments of gray ferberite- and marcasite-bearing horn quartz that it contains. The ferberite, pyrite, and marcasite are entirely unoxidized. The barren seal-brown quartz is earlier than small amounts of fine-grained light brownish gray horn, clear quartz, and barite.

In the Quaker City mine, barite is later than late clear quartz, brown horn quartz and ferberite, and is intergrown with a few crystals of galena and sphalerite. These minerals in turn are earlier than opal and a late white clay that is provisionally called beidellite, although it is made up of plates with a low birefringence and a refractive index of approximately 1.535.

It should be remembered that only in a few mines can any sulphides be found, and the total amount of pyrite, galena, and sphalerite is only a tiny fraction of the ferberite present. Still

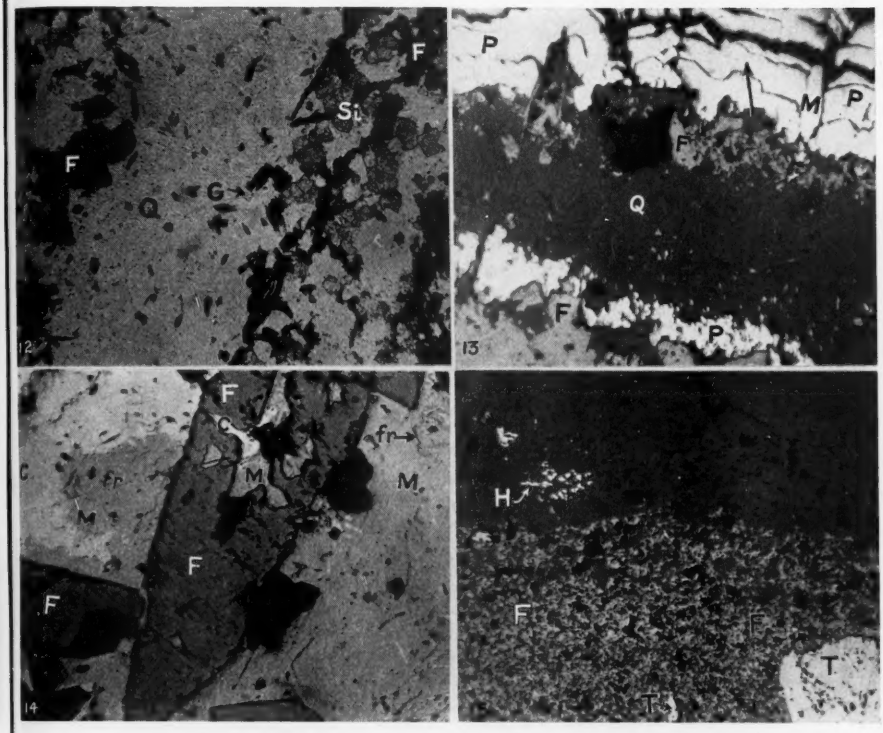

FIG. 12. Black horn quartz, 6 level, Coldspring mine. Contemporaneous siderite (Si) and ferberite (F) in quartz (Q) with goyazite (G). ×70.

FIG. 13. Ferberite ore from 5 level of Beddig mine. Successive layers of ferberite (F), pyrite (P), with minor marcasite (M), and quartz (Q). Arrow points toward center of vug. ×20.

FIG. 14. Ore from Illinois mine showing early ferberite (F) replaced by miargyrite (M) and chalcopyrite (C). Residual freibergite (fr) lies in the miargyrite. ×160.

FIG. 15. Ore from Dorothy mine, Millionaire Gulch. Early quartz and hematite (H), bordered by later quartz and ferberite (F), containing corroded fragments of tetrahedrite (T). ×40.

more unusual is the presence of other metallic minerals. Moreover, if the tungsten minerals are found in a silver or gold mine, it is generally difficult to tell whether the ferberite is a minor but unusual variant of the gold-silver vein or belongs to a distinct and separate epoch of mineralization. A similar problem presents itself for other ore minerals found in a tungsten mine. At two properties, however, the Illinois mine a mile northwest of Nederland and the L. Z. T. or Galenite adit in Gordon Gulch near the Primos School, the relations show silver minerals that essentially mark a closing stage of the ferberite deposition.

The Illinois mine is primarily a tungsten mine and has a considerable production to its credit. In one of its ore shoots, coarse-grained ferberite occurs at the junction of a minor east-west vein and a barren northwest slightly sheeted zone that has localized the ore. As the vein is followed away from the sheeted zone the tungsten ore becomes low-grade and sulphides appear. Generally there is a stretch of vein quartz, nearly barren of either sulphides or ferberite that is from ten to twenty feet long and separates the two types of ore, but in several places this transition zone is telescoped and both tungstate and sulphides are present. The width of the vein itself narrows from more than a foot at the sheeted zone to less than an inch fifty feet beyond the transition to the sulphides. The change from tungsten ore to silver ore is repeated on successive levels at about the same distance from the sheeted zone, which evidently guided the ascending metallizing solutions in the vein. It would seem that here the silver ore is a minor product of the tungsten stage of mineralization. As might be anticipated from the relative distance of the sulphides and ferberite from the structure localizing the ore shoot, the sulphides are mostly later than the ferberite and in only small part contemporaneous. A few grains of sphalerite have been found that appear to be contemporaneous with the ferberite. This relationship is rare and most of the sphalerite is later. In contrast, galena in minor amounts is often found contemporaneous with late coarse-grained ferberite. In the Galenite vein also, some galena was formed during the early stages of ferberite

deposition. This is the more interesting as most of the galena in both veins is later than the sphalerite. Tetrahedrite or freibergite is not uncommon with the ferberite of the Illinois vein and is later than the ferberite and early galena, but is replaced by miargyrite and chalcopyrite (Fig. 14). A second generation of miargyrite and chalcopyrite that may be supergene was seen in a few specimens, but it is believed that the first generation is hypogene. In sulphide ore from the Illinois vein the order of deposition is: (1) ferberite, (2) sphalerite and quartz, (3) freibergite, (4) miargyrite, (5) galena, (6) chalcopyrite, (7) miargyrite and polybasite, (8) chalcocite, and (9) bornite. Stages 8 and 9 are represented by minute veinlets near the surface only, and have not been seen in ore from more than a hundred feet below the surface. Probably much of the miargyrite and polybasite of stage 7 and some of the chalcopyrite of stage 6 are also supergene.

The L. Z. T. adit explores the Galenite vein in Gordon Gulch at the northern edge of the district, about 4 miles northeast of Nederland. It has produced little ore, but is one of the few properties in which ferberite is found intergrown with base-metal sulphides. In some ways the mineral sequence is even more revealing than that found in the Illinois vein. Successive layers of vein filling show an early period of brecciation followed by the deposition of quartz and marcasite. This sulphide-bearing quartz grades into nearly clean fine-grained quartz overlain by a narrow band of horn quartz that contains sparsely disseminated ferberite and galena. Locally a layer of dickite and goyazite is interposed between this band and the later main seam of ferberite and quartz. The dickite and goyazite are distinctly earlier than most of the ferberite. In the first part of the ore to be deposited the ferberite is sparsely distributed and coarser-grained than it is toward the center of the seam. A few minute pyrite crystals are scattered through the ferberite, and near the center and in the younger part of the ferberite layer small galena crystals are present. A microscopic vug in the seam of ferberite shows an outer layer of quartz containing a few ferberite crystals much coarser than the

average within the seam. Lying on this quartz are pyritohedrons of pyrite and cubes of galena. Banded gray horn quartz overlies the main ferberite layer and is barren of tungsten but contains disseminated pyrite and galena. The amount of these sulphides is greatest near the contact of the ferberite seam, and in the next layer, which consists of light gray, fine-grained quartz, galena is absent although disseminated pyrite is present. The succeeding layer of quartz is barren of all metallic minerals and lies against a silicified seam of breccia that contains fragments representing all the stages of vein filling described above. This breccia is cut by veinlets of sphalerite, galena, tetrahedrite, and quartz containing a small amount of pyrite, but the veinlets are truncated by a later clear vuggy quartz. The vugs are filled with an allophane-beidellite type of clay.

In a few other localities where the writer has seen galena and sphalerite associated with ferberite ore, both the sulphides are later than the tungstate. In specimens from several different mines a few grains of arsenopyrite have been found that appear to be nearly contemporaneous with the ferberite, but this relationship has not been fully established. They are in most cases associated with marcasite.

The Clay Minerals.—Most of the clay minerals found within the veins fall in one of four groups, but a few specimens contain clay minerals that differ from these common ones. Ranged according to decreasing indices of refraction they may be distinguished as dickite, beidellite, an amorphous clay mineral whose refractive index is close to 1.505 and which for convenience will be designated the 1.505 clay, and allophane.

Most of the vein dickite is earlier than the ferberite. Locally, as in the Conger mine, it is found in thin seams between first and second generations of ferberite, and in several veins it has been found resting on coarse vuggy ferberite. In the places where dickite rests on coarse-grained ferberite, the occurrences are very close to the bottom of ore shoots. Although this arrangement is suggestive, the number of such places is too small to warrant any generalization.

The most common clay mineral found in the tungsten veins is beidellite. This occurs in plates that show an average refractive index close to 1.54 when face up, but if rotated on their sides their indices are found to range from approximately 1.535 to 1.547. Everywhere that it has been found as a vein mineral beidellite is later than ferberite, but in the Grand Republic mine at the eastern end of the district, where a minor amount of ferberite has been found in a gold telluride vein, fragments of altered wall rock prove to consist largely of beidellite and are surrounded by concentric rings of marcasite, ferberite and pyrite. The post-sulphide clay mineral of the L. Z. T. prospect is largely beidellite. In the tungsten mines this mineral is abundant in the vuggy openings near the tops of ore shoots where it rests on uncorroded ferberite. Although later than ferberite, sulphides, and barite, it is earlier than or contemporaneous with late opaline quartz.

The 1.505 clay is nearly as abundant as the beidellite and is generally associated with it. It occurs in isotropic scales of irregular outline which commonly form the matrix in which the beidellite crystals are embedded. Its occurrence is the same as that of the beidellite. However, none has been found in the beidellitized fragments of altered granite in the Grand Republic vein, and the percentage of the 1.505 clay matrix varies greatly in different specimens.

The isotropic allophane occurs in minute blebs and irregular scales intergrown with the other clay minerals and is almost everywhere a minor constituent of the clay assemblages. In one specimen, however, nearly pure allophane with a refractive index of 1.48 was found lying at the edge of a vug between scheelite, which forms the center, and an earlier rim of pyrite crystals that rest on ferberite. In appearance, index, and size of grain it is identical with the early allophane seen in thin sections from altered wall rock near the outer edge of the zone of argillization.

In addition to the minerals described above, which are common throughout the district, a clay mineral with an index between 1.525 and 1.530 is found in a few places and is most common in

the Beaver Creek section of the district. It is probably a variety of beidellite and like it is later than the ferberite. Another post-ferberite clay mineral with a refractive index ranging from about 1.55 to 1.553 was found in the Coldspring mine.

All of the clay minerals described above have been found intergrown with one another in certain places, but generally dickite appears by itself or underlies a coating of the beidellite and allophane minerals.

Tellurides.—In the Harold mine in the eastern part of the district the writer discovered a small amount of ferberite-bearing quartz in what is essentially a gold-telluride vein. Polished sections of the ore showed that an early pyritic quartz mineralization was followed by brecciation, silicification, and the introduction of some ferberite-bearing horn quartz. The ferberite was followed by a layer of clear medium-grained quartz and this in turn by white, speckled, fine-grained horn quartz and barite, gold tellurides, and native gold. A milky horn quartz is later than the ore minerals. A specimen of telluride ore containing ferberite, which came from the Grand View mine in the Gold Hill district a few miles to the north of the tungsten belt and was lent to the writer by Mr. V. I. Noxon, contained abundant ferberite crystals embedded in moderately coarse-grained quartz that surrounded vugs filled with gold telluride. It would thus appear that in the normal sequence ferberite is earlier than gold telluride. However, the evidence given below indicates that the main tungsten mineralization may be later than the main gold telluride mineralization.

Although the Magnolia district, a short distance to the south of the eastern end of the main tungsten belt, is known chiefly for its gold-telluride ores, a minor zone of tungsten mineralization extends continuously from the main belt southeast into Magnolia. According to R. D. George,[17] "Ferberite is found with the telluride ore in the Graphic mine at Magnolia and a mine near Sunshine shows sylvanite associated with ferberite. Although the

[17] George, R. D., and Crawford, R. D.: The main tungsten area of Boulder County. Colo. Geol. Surv., First report, 1908: 76, 1909.

relative age of ferberite and sylvanite is not always clear, specimens of the Magnolia ore leave little doubt that so far as the occurrences there are concerned, the telluride is older. Porous quartz contains a sprinkling of sylvanite well below the surface and a crust of drusy ferberite covers the surface. The ferberite contains no telluride."

Specimens of telluride-bearing tungsten ore from the Kekionga mine of this district, given to the writer by Mr. George Teal, show a similar relationship. The order of mineral deposition in the Magnolia district according to Wilkerson[18] is as follows: 1, quartz; 2, quartz and hematite; 3, quartz; 4, quartz, pyrite, marcasite, and sphalerite; 5, fluorite (?); 6, calcite (?); 7, quartz, pyrite, alunite, and ferberite; 8, tellurides and native gold; 9, ferberite; 10, quartz, ferberite, and pyrite.

In an oral communication to the writer the late Mr. Fred Fair, mining engineer of Boulder, Colorado, said that ore from the Red Sign mine, one of the few properties that produced both gold and tungsten in commercial quantities, showed fragments of gold-bearing quartz cemented by ferberite at the intersection of a gold vein and a tungsten vein. In some specimens from this mine which were studied by the writer, fragments of the gold vein show abundant sylvanite in pre-ferberite quartz but none cutting the ferberite matrix. Furthermore, the tungsten ore cuts sharply through rich telluride ore (Fig. 16). It is believed that the somewhat meager evidence available indicates that commercial bodies of gold and tungsten ore were formed during two different successive epochs of mineralization, but that ferberite is precipitated before gold telluride within a single continuous stage of mineralization.

ORIGIN OF THE ORES.

Magmatic Source.—If the igneous rock genetically related to the tungsten ores is exposed, it is likely to be the one most nearly contemporaneous with them. The hornblende monzonite dikes

[18] Wilkerson, A. S., Telluride tungsten mineralization of the Magnolia mining district, Colo. ECON. GEOL., 34: 442, 1939.

in the western part of the district are displaced by about half the total movement along pre-mineral faults that contain unbrecciated ferberite ore. In contrast to them a biotite latite dike in the Eureka mine locally cuts across a tungsten vein and contains inclusions of granite that show alteration effects characteristic of the tungsten mineralization. The dike itself is slightly altered where it crosses the vein, but to a much smaller extent than the granite wall rock.

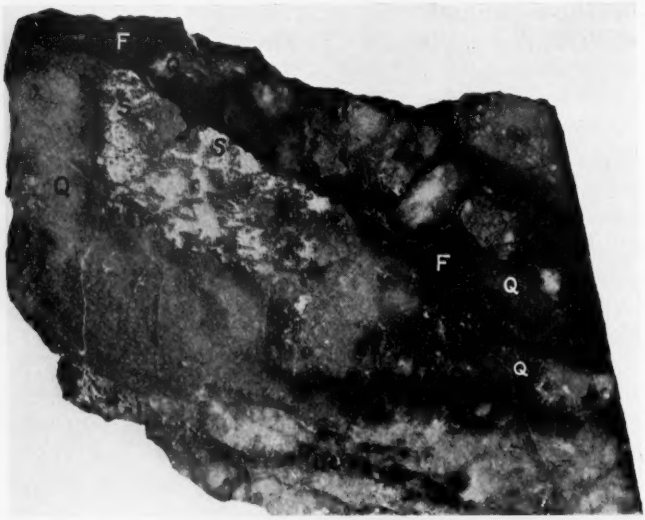

FIG. 16. Polished section of ore from Red Sign mine, × 3. Early quartz (Q), and sylvanite (S), are cut by a vein of ferberite-bearing horn (F). A narrow fragment of sylvanite may be seen surrounded by ferberite-bearing quartz, half way between the letters S and Q in the upper left corner.

In the Yellow Pine and Logan mines definite evidence was found that biotite latite and latitic intrusion breccia were intruded during one of the last of the movements that affected the veins. The dikes are apparently earlier than the gold-telluride ores but

contain fragments of early pyritic vein quartz. As the gold telluride and tungsten stages of mineralization were nearly contemporaneous, the possibility that the latites are genetically related to the tungsten ore immediately suggests itself.

The distribution of biotite latite dikes and gold telluride veins in the mineral belt of the Front Range is spotty but strikingly coextensive. This areal coincidence together with other factors has led to the suggestion that the ores were derived from the latitic magma.[19]

Valuable information is given by the extensive series of spectroscopic analyses of the Laramide and pre-Cambrian rocks from the mineral belt recently made by Dr. Joseph Bray and Dr. Richard Jarrel at Massachusetts Institute of Technology, and these results have courteously been made available to the writer. Of the Laramide intrusives tested, only the latite and latitic intrusion breccia contain a distinctive suite of siderophilic elements, including W, Ni, Cr, Cu, and Co. These elements are also present in the ferberite of the district. Although no silver was found in the gross samples of intrusion breccia from the Yellow Pine silver mine, tungsten was detected in one such sample. In magnetic concentrates from the intrusion breccia, tungsten, silver, lead, and copper were found. It is of especial interest that oligoclase-andesine from the massive biotite latite shows no tungsten but contains a definite trace of both silver and copper. Fire assay by Mr. E. T. Erickson of the Geological Survey, showed 0.01 ounce of gold to the ton in the intrusion breccia and a trace in the massive biotite latite dike. A trace of tungsten was reported in this rock by Dr. Bray. None of the 40 other rocks tested contained tungsten or gold, not even the strongly altered wall rocks of the tungsten veins. The freshness of the sample of intrusion breccia, the fact that it was taken where there was no evidence of mineralization and some distance from a recognized vein fissure, and the meagerness of its silver although taken in a mine that has produced silver-bearing gray copper ore with a total value of sev-

[19] Lovering, T. S., and Goddard, E. N.: Laramide igneous sequence and differentiation in the Front Range, Colo. G. S. A., Bull. 49: 65, 1938.

eral hundred thousand dollars, all point to the primary nature of the elements found in it.

Evidence that the latitic magma was the source of mineralizing solutions is also found in the character of the wall rock alteration associated with latite dikes. The fresh biotite latite contains a remarkably high concentration of volatiles (4.06 H_2O+ and 4.60 H_2O-). The explosive violence with which thin persistent seams of breccia-charged latite must have been emplaced indicate a magmatic reservoir in which a tremendous vapor pressure had been generated. It is not surprising that these rocks are commonly altered and are generally associated with mineralized fissures.

Just east of Switzerland Park in the central part of the district, a short adit on the Lou Dillon claim exposes the top of a biotite latite dike and its associated intrusion breccia, and gives valuable information on the character of the fracturing and alteration that accompanied their intrusion. The biotite-latite porphyry dike, which shows only at the portal of the tunnel, was intruded along a strong fault zone that strikes N. 30° E. and dips 70° N.W., but the dike has not been found elsewhere in the fault. The porphyry is moderately fresh and is the hangingwall of a nearly parallel seam of latitic intrusion breccia. The linear structure within the latite dike and the intrusion breccia pitches gently to the southwest. This fact and the absence of the dikes at the surface southwest of this outcrop indicate that the exposure is close to the top of an intrusive mass. As the latitic breccia is followed to the southwest in the adit, it curves south and southeast away from the biotite latite porphyry along a gently sloping fracture that dips 35–65° west. The fracture rapidly weakens as it is followed south and disappears near the breast of the drift, a short distance south of the point where the intrusion breccia itself pinches out. The feathering out of the fracture leads the writer to conclude that it was formed as a result of the intrusion of the porphyry.

The wall rock contains some marcasite and hematite and is slightly bleached close to the biotite latite porphyry and the intrusion breccia, but along the thin fracture that persists a short dis-

tance beyond the intrusion breccia strong argillic alteration gives way to that typical of the sericitized "casing" that encloses the tungsten veins of the district, and here sericitization was accompanied by pyritization but not by introduction of ferberite. The wall-rock alteration is more intense close to the intrusive breccia than at a distance and argillization occurs closer to the dike than does sericitization. The general relations indicate that the alteration was due primarily to solutions coming from the intrusion breccia or rising through it from the same source magma soon after its emplacement. It is believed that argillization occurred close to the hot intrusion breccia immediately after its introduction, while sericitization was taking place a short distance away where the solutions were cooler.

Character of the Solutions.—The chemistry of the mineralizing fluids must be inferred largely from the minerals precipitated and certain of them are much more significant than others. The clay minerals have already been discussed, and of the other minerals found as vein filling marcasite and pyrite are most diagnostic of the solutions.

The work of Allen, Crenshaw, and Johnston [20] on the iron sulphides establishes the fact that at a given temperature the proportion of iron sulphide precipitated as marcasite instead of pyrite is almost a linear function of the final acidity of the solutions. Cold solutions that were sufficiently acid gave marcasite, but at higher temperatures solutions of the same pH yielded an increasing proportion of pyrite. Pyrite alone was precipitated from hot solutions that were either neutral or alkaline. The effect of the two variables, acidity and temperature, is indicated by Tables 2 and 3 which are taken from their excellent paper. Table 3 shows clearly that, if the pH remains constant but slightly on the acid side, a decreasing temperature favors the precipitation of marcasite rather than pyrite. Allen and his colleagues believed that the relation of pyrite to marcasite was an allotropic one and

[20] Allen, E. T., Crenshaw, J. L., and Johnston, John: The mineral sulphides of iron with crystallographic study by E. S. Larsen. Amer. Jour. Sci., 33: 169–236, 1912.

TABLE 2.

THE EFFECT OF FREE SULPHURIC ACID ON THE FORMATION OF MARCASITE AND PYRITE.

$NH_4Fe(SO_4)_2 \cdot 12H_2O$	H_2O saturated with H_2S	Free H_2SO_4	Per cent of pyrite in precipitate
5 grams.....	100 c.c.	.50 g.	43
5 grams.....	100 c.c.	.57 g.	25
5 grams.....	100 c.c.	.78 g.	10
5 grams.....	100 c.c.	1.18 g.	7.5

TABLE 3.

EFFECT OF TEMPERATURE ON FORMATION OF MARCASITE AND PYRITE.

$FeSO_4 \cdot 7H_2O$	Sulphur	H_2O saturated with H_2S	Free H_2SO_4	Per cent of pyrite	Temperature
5 g.....	.5 g.	100 c.c.	0.17 g.	57.5	300° C.
5 g.....	.5 g.	100 c.c.	0.17 g.	56.5	300° C.
5 g.....	.5 g.	100 c.c.	0.17 g.	32.0	200° C.
5 g.....	.5 g.	100 c.c.	0.17 g.	6.0	100° C.
5 g.....	.5 g.	100 c.c.	0.17 g.	10.0	100° C.

demonstrated that marcasite changes to pyrite at about 450° C. However, it is difficult to understand the precipitation relation given above if both minerals are allotropic forms of the same compound. Recent work by Buerger [21] leads him to conclude that pyrite and marcasite are chemically different. He believes pyrite is pure FeS_2 but that marcasite is a compound low in sulphur and high in iron whose general formula is $Fe\left|\begin{matrix}Fe_x\\S_{2-x}\end{matrix}\right.$ where x is approximately 0.004. According to Lindgren, "Marcasite forms only in acid solutions." [22] However, W. H. Newhouse studied a number of marcasite occurrences where the mineral was developed by a late-stage replacement of pyrrhotite and is associated with carbonate minerals that seem in part contemporaneous, though most of them are definitely later than the marcasite. This association led him to conclude that marcasite may develop in nearly neutral solutions.[23] In the Goldfield district where Ran-

[21] Buerger, M. J.: The pyrite-marcasite relation. Am. Min. 19: 37–47, 1934.

[22] Lindgren, Waldemar: Op. cit., p. 830.

[23] Newhouse, W. H.: Paragenesis of marcasite. ECON. GEOL., 20: 54–66, 1925.

some ascribed the extensive silicification and alunitization of the wall rocks to acid solutions active during the period of ore deposition, subsequent work on polished sections by Tolman and Ambrose showed that pyrite with minor amounts of contemporaneous marcasite were introduced at the time of the alunitization and silicification.[24] It would seem that conclusions drawn from the experimental work done in the Geophysical Laboratory can be safely used in the interpretation of the character of solutions that deposit marcasite and pyrite.

Alunite itself has been accepted generally as proof of acid solutions because of its known origin at Tolfa where it is formed by the action of sulphuric solutions on trachyte.[25] Ransome's assignment of the alunite of Goldfield to acid sulphate solutions has not been questioned, although the origin of the acid solutions may still be debated. The closely related goyazite so abundant in the early vein quartz of the tungsten belt has been reported from few other localities. It is usually found in pegmatites and is associated with relatively high-temperature assemblages. Svanbergite, the less closely related member of the alunite group, is found in crystalline schists and gneisses near Lake Wenner in southern Sweden, where it is associated with hematite, lazulite, pyrophyllite, damourite, and kyanite. It is also reported from the iron mine of Westana Scania, Sweden, where the mineral composition is similar.[26] The presence of damourite and pyrophyllite suggests hydrothermal solutions and the hematite indicates that they were oxidizing and probably acid in character.

The marcasite and dickite of the Boulder County tungsten veins may be taken as sufficient evidence to establish the acid character of the solutions that preceded the ferberite mineralization, and the abundance of sulphate-bearing goyazite and the widespread but

[24] Ransome, F. L.: The association of alunite with gold in the Goldfield district, Nevada. ECON. GEOL., 2: 687–692, 1907; Tolman, C. F., and Ambrose, J. W.: The rich ores of Goldfield, Nevada. ECON. GEOL., 22: 264–265, 1934.

[25] DeLaunay, L.: La Metallagenie de l'Italie. Cong. Int. Geol., Mexico, 1906, I: 681, 1907.

[26] Dana, E. S.: A system of mineralogy, 6th edit., 1892, pp. 855, 868.

meager hematite furnish coroborative evidence of the acid character of these solutions.

In many specimens ferberite is intergrown with siderite and sparse goyazite in layers that alternate with ferberite-free quartz that contains abundant goyazite. Even more significant is the change in the iron sulphides that preceded and accompanied the deposition of ferberite. As noted earlier, the transition from the early marcasite-bearing quartz to ferberite ore is everywhere accompanied by the appearance of pyrite and the diminution in the proportion of marcasite present, and generally by the complete disappearance of this acid-indicating sulphide. The study of the marcasite-pyrite relation in polished sections representing mines scattered throughout the district emphasizes the fact that pyrite is the characteristic contemporaneous iron sulphide and that in the rare specimens that show a reappearance of an increasing marcasite-pyrite ratio, the ferberite rapidly diminishes in amount although coarsening in grain. The paragenesis points definitely to a generally decreasing acidity during mineralization and to the precipitation of tungsten when the solution was almost at the neutral point although slightly on the acid side.

In the laboratory, ferric hydroxide is precipitated when an acid solution containing ferric ions is neutralized or made alkaline, but it may also form slowly by hydrolysis in very weakly acid solutions. The conditions that caused the hypogene iron hydroxide to precipitate and form the brown horn quartz halted ferberite deposition. It seems very probable that this brown hydroxide reflects a shift from slightly acid to a neutral or alkaline environment. The disseminated pyrite in the brown horn quartz shows that some of the iron was present in the ferrous state, but the precipitation of the hydroxide indicates that an appreciable part of the total iron carried by the acid solutions was in the ferric state.

The shift from slightly acid to neutral or alkaline conditions, indicated by the brown horn quartz, is believed to coincide with the beginning of the late sericitic alteration. It is in the narrow sericitized casing that late adularia is commonly found replacing

the minerals formed during the early cycle of alteration. In the vein filling adularia is also a late mineral and is generally contemporaneous with or later than the post-ferberite barite. Although some sericitization of the walls and rock fragments in the veins took place prior to ore deposition, a large proportion of the mineral that was first regarded as sericite in the fragments proved to be a hydrous mica of slightly lower refractive index and birefringence. It is believed that the adularia and most of the true sericite formed after the ferberite was deposited, but the evidence for post-ferberite sericitization is not decisive. The characteristic post-ferberite clay minerals are those of the beidellite-montmorillonite group, and Noll's experimental work leads to the inference that their development is favored by nearly stagnant alkaline solutions such as would mark the end of mineralization. The cumulative evidence is strong that ferberite was not deposited when the solutions became definitely alkaline.

The chemical composition of the different solutions is suggested by the vein filling and the altered wall rock. They were evidently rich in silica, potash, and sulphur acids, and carried iron and tungsten in moderate amounts together with appreciable amounts of strontium and phosphoric acid. Some barium, carbon dioxide, fluorine, and hydrogen sulphide were also present, as well as very small amounts of lead, copper, silver, antimony, and zinc. The early strongly acid solutions attacked the granite wall rock with vigor and dissolved much silica, soda, and lime as well as some magnesium. Such reagents would decrease the acidity of the solution and eventually result in its becoming alkaline.

Mineral Equilibria.—Where ferberite is in contact with tetrahedrite or freibergite one or the other shows evidence of corrosion. If the tetrahedrite is the later as it is in the Clyde, Illinois, and L. Z. T. properties, the ferberite crystals have ragged edges and are replaced by tetrahedrite. If the ferberite is later, as it is in the Dorothy mine at the extreme eastern edge of the district, the tetrahedrite is present as corroded fragments and the ferberite crystals are euhedral (Fig. 15). In contact with siderite, ferberite shows no corrosion, but where calcite comes against

it, both the ferberite and the associated quartz crystals may be strongly etched. Although most of the dickite is earlier than the ferberite, late dickite is not uncommon. It commonly rests on coarse but perfect ferberite crystals, but in some places the ferberite shows corroded edges against the dickite. In many places quartz or opal has been deposited on strongly corroded ferberite.

Vuggy barren vein matter found on the Clyde dump shows innumerable hollow molds of coarse ferberite crystals. A thin shell of fine-grained quartz, barite, beidellite, and opal was deposited on ferberite crystals, preserving their form perfectly, although in the hundreds of shells examined only a few ferberite crystals still remained as cores. Barite is abundant in well-formed crystals on the barite-silica shells and was probably deposited by the solutions that redissolved the ferberite. Barite crystals of the same type are conspicuous in an open barren rubble-lined portion of the vein between two large ore shoots on the 200-foot level. Here, large irregular fragments are heavily coated with clay minerals. The downward-facing sides of the fragments have a crust of impure dickite from one-half to one and a half centimeters thick, suggesting active upward circulation of acid solutions, but the crust on the upper side contains little dickite, is chiefly made up of barite and quartz, and probably reflects sluggish movement of the solution. A light coating of clay with a refractive index of 1.525 rests upon these siliceous crusts locally. The openness of the fissure and its direct connection with the ore shoots on either side indicate that the mineralizing fluid must have had access to it at the time when the adjacent ferberite ore was being deposited. It would seem, however, that the conditions that favored the deposition of barite, dickite, and the 1.525 clay were unfavorable to the precipitation of tungsten. It has already been pointed out that the conditions that favored the precipitation of marcasite did not favor the precipitation of ferberite, and, from the corrosion of the ferberite in contact with tetrahedrite, it would seem that not only were the solutions that deposited the gray copper inimical to the precipitation of ferberite but that they actually favored its solution.

Chemistry of Mineralization.—Both phosphoric acid and sulphuric acid are excellent solvents for tungstates.[27] A weak acid such as tungstic acid would be expected to be precipitated near the neutral point if ferrous ions were present, but ferric iron on the contrary should have no precipitating effect.[28] If the solutions became alkaline the ferrous ion would no longer be capable of precipitating the tungstate and a stronger base such as calcium would be required, according to Professor Willard. This prediction harmonizes with the universal occurrence of scheelite as a late mineral in the tungsten district; however, it apparently conflicts with the conclusion reached by Gannett,[29] who reported that he was unable to precipitate ferrous tungstate in acid solutions but almost completely precipitated it by making ferrous sulphate-tungstic acid solutions slightly alkaline with sodium hydroxide. Ferric chloride in slightly acid solutions completely precipitated the tungsten as a hydrous ferric tungstate. He found that sulphuric acid alone and in combination with sulphates of calcium, sodium, manganese, and ferrous iron attack sheelite, wolframtie, and ferberite, but the presence of ferric salts inhibited the solvent action or greatly reduced it. Sodium acid carbonate had no effect on the minerals but sodium hydroxide solutions attacked both wolframite and ferberite slightly.

The discrepancy between the chemistry inferred from the field evidence and that suggested by Gannett's work led the writer to make some tests on the behavior of ferberite in hot solutions. It was found that a boiling solution containing 10 per cent phosphoric acid and 10 per cent sulphuric acid (by volume), readily decomposes ferberite with resulting solution of its tungsten. The addition of potassium sulphate alone causes the complete precipitation of potassium phospho-tungstic acid as a fine white precipitate. The addition of sodium sulphate with the potassium

[27] Moore, R. B., and others: Analytical methods for certain metals. U. S. Bur. Mines, Bull. 212, Part IV, Tungsten, by C. W. Davis, pp. 131–167, 1923.

[28] Willard, W. H.: Personal communication.

[29] Gannett, R. W.: Experiments relating to the enrichment of tungsten ore. ECON. GEOL., 14: 68–78, 1919.

sulphate inhibits the precipitation and with slight dilution prevents it altogether.

If the phosphoric-sulphuric acid solution is cooled and is made alkaline with sodium carbonate a greenish precipitate of ferrous hydroxide forms at the neutral point, but gray ferrous carbonate is quickly formed and the ferrous hydroxide is all converted into ferrous carbonate on boiling under petrolatum. The filtrate gives a strong positive reaction for tungsten with stannous chloride and the precipitate a weak one. When the acid tungstate solution was made very slightly alkaline with sodium hydroxide a greenish curdy precipitate of ferrous hydroxide formed. After heating the solution and the precipitate under petrolatum on a sand bath for 18 hours, the hydroxide was filtered off, dissolved in hydrochloric acid and tested with stannous chloride. No tungsten blue was formed, but the filtrate from the hydroxide gave a strong positive test for tungsten. When the acid tungsten solution was almost neutralized with Na_2CO_3 but still acid to litmus paper a heavy floculent dark blue precipitate of W_2O_5 formed. When NaOH was used instead of Na_2CO_3, a bluish-gray precipitate formed in the slightly acid solution and, after boiling for 24 hours, both the precipitate and filtrate gave a strong test for tungsten. This laboratory work supports the conclusions reached independently from the field observations.

If in the tungsten veins acid solutions became neutralized and then rendered alkaline largely through the addition of soda, the tungsten in the alkaline solutions would be converted into the soluble sodium tungstate and would not be precipitated even as scheelite except under very special conditions. Although sodium tungstate is very soluble and tungstic acid is readily converted into it by neutralizing with sodium carbonate, ferrous tungstate (ferberite) is difficulty soluble, and like quartz, once formed would be redissolved very slowly. The field evidence discussed under *mineral equilibria* is compatible with the portion of Gannett's laboratory work dealing with the solution of ferberite and indicates that acids were more effective than the alkaline sodium-rich solutions in dissolving the ferberite. One con-

dition essential to the formation of ferberite is the presence of ferrous ions. In veins where both siderite and sulphides are so meager it may be that locally all the ferrous ion was used up in the precipitation of the tungsten. Thus, even after an alkaline condition had been reached, a considerable amount of tungsten may have remained in solution as soluble sodium tungstate because any ferrous ions present were insufficient to precipitate the tungstate completely when the solutions became neutralized.

With the general chemistry in mind a plausible interpretation of the wall-rock alteration and the paragenesis of the vein filling may be made. The extensive clay-mineral alteration along the major channels of mineralization gives some conception of the strength of the hypogene acid solutions and the length of this pre-ore stage of hydrothermal activity. The succession of the clay minerals in the wall rocks is in harmony with Noll's [30] experimental work. Close to the vein, where the solutions were most acid and the circulation was best, dickite formed. At greater distances beidellite appeared, and in the outermost sub-zone, where circulation was negligible, only allophane and sericite developed. If the solutions were derived from a biotite latite magma immediately after the explosive introduction of the intrusion breccias, the hot emanations must have had a high propelling force at the beginning of the period of mineralization, but this force would be expected to diminish rapidly. The curve representing the rate of flow with time, should be very similar in form to that of the production-decline curve of an oil well that has been allowed to flow freely. Under such conditions the temperature of the wall rocks would increase rapidly to a maximum and then commence to fall slowly.

The constant shifting of the major channels of circulation, owing to the intramineralization movement of the faults so plainly recorded in repeated brecciation, would allow the alternate cooling and heating of different areas of a vein and was probably an important factor in the precipitation of the vein minerals. As shown in Fig. 10, the attack of the acid waters on the granite

[30] Noll, W.: Op. cit.

removed substantial amounts of silica. Silica may be deposited from acid solutions of almost any strength through the simple mechanism of cooling or increasing pH, and it is reasonable to suppose that much of the silica deposited in the vein was derived from wall rock altered at slightly greater depth by hot rising solutions that cooled as they rose. At a given point many fluctuations in the temperature of solutions passing would be likely to occur, and deposition, non-deposition, or even solution of material might alternate. The quartz may be pictured as depositing in a shifting but generally descending zone of precipitation along intermittently active fault zones (Fig. 17). Although it is known

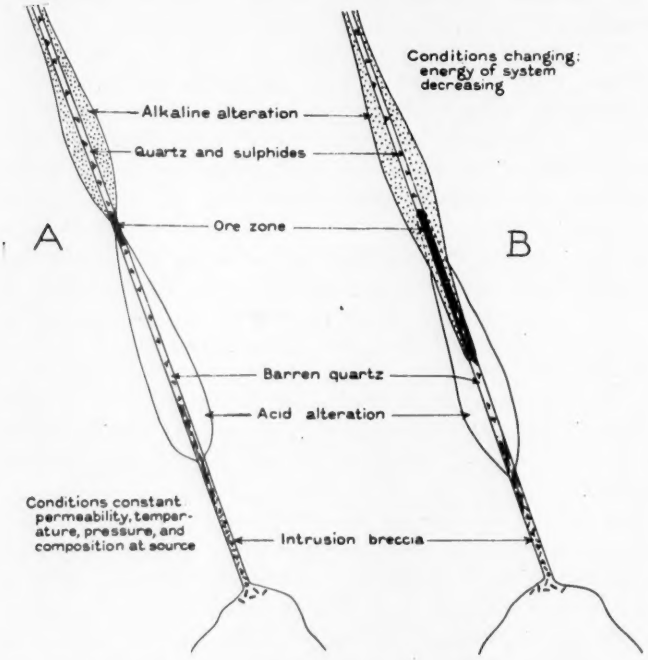

FIG. 17. Diagram representing conditions during early stage of mineralization, A, and late stage of mineralization, B.

that many silicates are readily soluble in acid solutions, quartz, once it is deposited as such, is much more stable.[31] Thus, after the leaching of silica from the wall rocks and its redeposition along intermittently cooler or less acid places in the vein, quartz might remain unattached, even though the solutions became either hotter or more acid temporarily.

It is of interest to note that a change of a mol of oligoclase to a mol of beidellite involves neither gain nor loss of silica and alumina, but that the change from oligoclase to dickite liberates about 20 per cent of the silica present in the feldspar. This is in harmony with the relative losses of silica in the dickite and beidellite sub-zones, as shown by the analyses.

It would be expected that under the conditions outlined above the vein quartz would give way at depth to a zone of intense argillic alteration. One of the most intensely altered zones in the district is found along the Madeline vein a short distance to the north of the Coldspring mine, and, although much exploration work was done along the vein, almost no ferberite has been produced. A strong vein of horn quartz was found to bottom abruptly in soft argilliferous gouge about a hundred feet below the surface. Commercial bodies of ferberite have been found in branch fractures in the hangingwall of the strongly altered fault zone but not along what would appear to be the main channel of mineralization.

The relation of the ferberite to the sulphides of iron, lead, zinc, and copper and to the silver sulphantimonides, sheds some light on the chemistry of the deposition of these ores. The contemporaneity of arsenopyrite and a minor amount of galena with ferberite suggests they may be precipitated in neutral or slightly acid solutions; however, by far the greater part of the galena is later than sphalerite and tetrahedrite and like them was precipitated from alkaline solutions. The copper and silver sulphides and sulphantimonides were probably precipitated from

[31] Lovering, T. S.: The leaching of iron protores: solution and precipitation of silica in cold water. ECON. GEOL., 18: 530, 1923.

alkaline solutions of higher pH or lower temperature than obtained when the precipitation of sphalerite and galena began.

Generation of the Acid Ore-forming Solutions.—In considering the origin of the acid waters that caused the alunitization of Goldfield, Ransome first favored the theory that they were derived from the initially acid emanations of a dacitic magma that were neutralized and modified in their ascent through fissured rock where they deposited the ores and induced the alteration for which the district is famous.[32] Later, however, in an effort to make the origin of the Goldfield deposits more nearly compatible with that accepted for the carefully studied ores of Tonopah, Grass Valley, and Cripple Creek, he advocated the theory that ore constituents were brought up by hot solutions charged with hydrogen sulphide, carbon dioxide, and some alkali sulphide; that the hydrogen sulphide was oxidized on and near the surface to sulphuric acid which percolated down through the warm rock and mingled with the uprising currents; and that the precipitation of the richest ore took place as a consequence of this mingling in the zone where the two kinds of solutions met.[33]

In the Boulder County tungsten district there is no such evidence of an abundance of hydrogen sulphide in the rising solutions as may be inferred from the sulphides associated with the Goldfield ores. Thus the character of the mineralizing solution seems to preclude appeal to the oxidation hypothesis suggested by Ransome, and the source of the acidity must be sought elsewhere.

Graton[34] has recently presented the results of an extended study of the nature of the ore-forming fluids, and has reached the conclusion that they always leave the magma as an alkaline liquid. Such districts as Cerro de Pasco, Goldfield, Bonanza, and Boulder County, where the action of hypogene acid solutions has

[32] Ransome, F. L.: The association of alunite with gold in the Goldfield district. ECON. GEOL., 2: 69–692, 689, 1907.

[33] Ransome, F. L.: Geology and ore deposits of Goldfield, Nevada. U. S. Geol. Surv. Prof. Pap. 66: 193, 194, 195, 1909.

[34] Graton, L. C.: Nature of the ore-forming fluid. ECON. GEOL., 35: 197–358, 1940.

been recognized, are explained by Graton as due to the formation of acid in originally alkaline solutions through the appearance of a gas phase, according to some such reaction as:

$$4H_2O + 4S = 3H_2S + H_2SO_4.$$

This reaction is induced by the low pressures in the upper part of the conduit according to Graton and would normally result in late acid alteration superposed on early alkaline alteration. Where acid attack has been followed by alkaline alteration, as at Bonanza and Boulder County (and Goldfield?), it is assumed that H_2SO_4 was developed so early that little alteration had been accomplished by the previously alkaline solution. This early abnormal acid production is supposed to give way to a normal alkaline condition later.

Graton's adroit manipulation of the physical, chemical and field data, is very persuasive. Some of his most compelling reasons for abandoning the theory that the ore-forming fluid may leave the magma as an acid emanation are listed below.

1. Steam either above or below the critical point is an extremely poor carrier of either the volatile or non-volatile compounds of the magma.

The vapor pressure of the volatile halides would indicate that almost all of the F and Cl would come off in combination with H as HCl and HF and not in combination with the metals. In the case of the vast amount of ore in a single deposit such as Cerro de Pasco, the facts just cited make it seem most improbable that transport of silicon and the ore metals was accomplished as gaseous halogen compounds.

2. The high latent heat of steam and the low conductivity of rocks makes it unlikely that any condensation of gas to liquid would take place once boiling has started. The importation of heat would be faster than the rock's ability to carry it off and a gas phase would soon exist all the way to the surface. This would preclude the liquid phase recognized as being present during ore deposition.

3. When a body of magma reaches the surface a very different

temperature-pressure balance is effective from that operating in the more confined magmas from which ore-forming solutions come. Thus, the presence of volatile halides of the metals in volcanic emanations affords no safe index of how these same volatiles escape at depth.

Argument 1, which assumes that the halides available in a magma could not transport the vast quantities of metal represented by a single large sulphide deposit, is difficult to prove but seems very reasonable; however, the ferberite deposits and the gold-telluride deposits are distinguished from most ore deposits by the meager amount of metal actually present. The entire production of tungsten from Boulder County amounts to only 17,000 tons of ferberite. The metallic minerals associated with the gold tellurides are insignificant if pyrite and marcasite are neglected, both of which may have formed in part from iron leached from the walls at depth. Thus, if argument 1 is accepted at face value, it supports the conclusion that the Boulder County ores were derived from emanations leaving the magma as a gas phase, and gives an explanation of the paucity of associated metallic minerals.

Argument 2 neglects certain vital factors such as cooling due to expansion and cooling due to entrance into bifurcating channels and the consequent contact with larger areas of rock as the vapor moved away from the magma. The cooling due even to adiabatic expansion from a pressure of several thousand pounds to a pressure of several hundred would be measured in hundreds of degrees. Entrance into branching channels would slow down the movement of the vapor and increase the area of contact, both factors working toward cooling and condensation.

Argument 3 apparently springs from the conviction that all magmas that generate ore-forming solutions are deep magmas and the present writer does not share this belief. If the Cerro de Pasco source magma has been intruded to the level where hypogene acid alteration has taken place, and if, as assumed by Graton, acid was formed in the ore-forming solutions owing to the appearance of a gas phase, it would seem inevitable that the magma

itself at this higher level would send off acidic gas-phase emanations. The acid alteration apparently extends to a level at least three thousand feet below the surface that existed during mineralization at Cerro de Pasco. The evidence in this South American district as to the depth of acid alteration, together with the data collected at Katmai as to gas-phase transport leads to the logical conclusion that acidic gaseous metal-bearing emanations may be given off by magmas several thousand feet below the surface.

The relation of the ferberite and gold-telluride deposits to the porphyries of the Laramide porphyry belt and the lack of any surface forms of volcanic nature, such as are found with post-Eocene volcanic activity wherever it is known elsewhere in the Front Range, affords strong presumptive evidence that the veins were formed during late Laramide time. So far as the writer is aware no one has yet suggested that his interpretation of the physiographic history of the region has erred on the side of ascribing too little erosion since Eocene time.[35] It is believed that the position of the surface at the time the deposits were formed must have been 2,000 feet or more above the present one. Pressures in gougy fissures at such a depth might have been relatively high but the sensitiveness of ore shoots to the presence of gouge in the veins indicates that relatively open channels were available and that the pressures driving the solutions upward were not abnormally large. Low pressures are also indicated by the lack of fluid inclusions in the quartz and by the mineral assemblage. Emanations derived from the explosively implaced intrusion breccia may very reasonably be assumed to have had an extremely high initial pressure. The low pressures in the fissures above would almost certainly induce a gas phase, and here expansion must have caused a rapid drop in temperature. Such a gas phase would inevitably be acid in character.

According to the work of Allen and others, marcasite changes to pyrite at 450°, and its presence fixes an upper limit of the tem-

[35] Rich, J. F.: Comment on "Physiographic development of the Front Range" by F. M. Van Tuyl and T. S. Lovering. G. S. A., Bull. 46: 2046–2054, 1936.

perature at which the ores were formed. The presence of dickite indicates temperatures too cool for the formation of nacrite but too hot for kaolinite. The associated sphalerite, galena, tetrahedrite, miargyrite, polybasite, and freibergite are suggestive of epithermal conditions, but represent solutions distinctly cooler than those that deposited the ferberite. Judging by the gauge pressure of saturated steam,[36] the maximum temperature of a dilute aqueous liquid solution under a hydrostatic pressure of 2,000 feet would be approximately 275° C. It is suggested that the temperature at which the ferberite formed was between 200° and 300° C.

When thoughtfully analyzed, Graton's arguments against the reality of acidic, gas-phase, metal-bearing magmatic emanations, either break down or actually lend strong support to the inference that just such a mechanism was responsible for the Boulder County tungsten deposits. Although realizing that Graton's conclusions may apply to the majority of ore deposits, the writer believes that the field relations and the paragenesis of the ores described in this paper are most logically explained as due to the action of a condensate from initially acid gas-phase metalliferous emanations derived from a latitic magma.

Conclusion.—The gold-telluride deposits locally contain minor amounts of ferberite and are closely related to the tungsten deposits mineralogically and spatially. Evidence has been presented that both the gold-telluride and tungsten deposits are genetically related to the introduction of latitic intrusion breccia. The earliness of the acidic alteration and its apparent increasing intensity with depth support the inference that the solutions were acid at their source. The meagerness of associated sulphides suggests gas-phase transport when they parted from the magma. The explosive violence that is evident in the emplacement of the latite intrusion breccia leads to the belief that the emanations separated from the magma as a gas-phase carrying water, tellurium, and sulphur, with gold and tungsten halides, and rose through conduits

[36] Hodgman, C. D.: Handbook of Chemistry and Physics, 19th edit., p. 1273, 1934.

of hot porous latite breccia in this condition, but condensed upon entering the cold fissures above the intrusion breccia. The mineral composition of the deposits indicates that these acidic aqueous solutions eventually became alkaline through reaction with the wall rock and that ferberite precipitated as the liquid approached the neutral point, whereas the gold tellurides were not deposited until after the solutions had become alkaline.

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Oct. 1, 1940.

ORIGIN OF THE SURIGAO IRON ORES.[1]

DEAN F. FRASCHÉ.

ABSTRACT.

The iron-ore deposit of Surigao, Mindanao, occurs as a surficial mantle over serpentinized ultrabasic rocks. Evidence is presented to show that the iron-ore is lateritic in origin, having been derived by process of subaerial decomposition of the parent serpentine rock. The theory of origin is substantiated by field studies, mineralogical, and chemical data, which make it possible to show the gradual alteration of the serpentine rock to iron-ore. The Surigao deposit is compared with the lateritic iron-ores of Mayari, Cuba, which it closely resembles.

INTRODUCTION.

SINCE the inauguration of the Commonwealth of the Philippines and the reorganization of the Bureau of Mines, much emphasis has been given to the development of the mineral resources of the Philippine Islands. One of the outstanding government activities has been a re-study of the extensive iron deposits within the government reservation in Surigao Province, Mindanao. Although these iron-ores were discovered in 1912 and a preliminary survey of them made in 1915, it was not until 1937 that they were surveyed in detail. During the latter year the government-controlled National Development Company, in close cooperation with the Bureau of Mines, commenced an exploration program of the deposits in the vicinity of Dahican Bay, Surigao. This program consumed almost a year, during which time 50,000,000 metric tons of uniform grade ore were developed and blocked out by drilling in an area containing a possible total of 1,000,000,000 tons within the Surigao reservation. Thousands of samples were taken and analyzed, and detailed studies were made of the physical nature and origin of the ores. It is proposed here to

[1] Read before the Fifth Philippine Science Convention, Manila, February, 1939.

discuss the origin of the Surigao iron-ores rather than their commercial possibilities.

The iron ores are in situ and are lateritic[2] in origin. Petrographic and chemical evidence shows that they were derived by processes of weathering from a serpentinized peridotitic rock. Because of their remarkable similarities the Surigao laterites are compared with those found in the Mayari district, Cuba.

The writer gratefully acknowledges the assistance given him by Mr. Jose B. Barcelon of the Bureau of Mines. The results of his laboratory studies have been invaluable in preparing this paper. For helpful suggestions and criticism the writer is indebted to Dr. H. Foster Bain, Mr. A. F. Duggleby, Dr. Robert Overbeck, and Dr. Andrew Leith.

Location.—The Surigao iron-ore deposits are situated in the northeastern part of the Province of Surigao, Mindanao, within the government reservation outlined in Fig. 1. The reservation, created in 1914, embraces the territory between the Pacific coast of Surigao, extending south from Gigaquit and a line running west from Cantilan, or between 125° 41′ and 125° 58′ east longitude, and 9° 20′ and 9° 36′ north latitude (Fig. 1). The reservation covers 587 square kilometers, of which area approximately 150 square kilometers are covered by iron-ore. The barrios Gigaquit, Claver, Taganito, Adlay, Carrascal, and Cantilan, are located on the coast within the Surigao reservation. The barrios of Adlay and Carrascal are situated on Carrascal Bay.

Climate.—The climate of the eastern part of Surigao is tropical and is divided into a wet and dry season, the wet season occurring from October to April, the dry taking up the remainder of the year. During the wet season the region is swept by the northeasterly monsoon. About February the wind generally shifts to the southwest, the monsoon blowing from that direction across the China Sea toward Mindanao. Recorded rainfall for Surigao, Surigao, is as follows:

[2] Laterite is here used in the sense that it is a mixture of ferric and aluminum hydroxides and oxides, and free silica in varying proportions, which has originated in situ from the atmospheric weathering of rocks.

PHILIPPINE ISLANDS
SCALE
BALINTANG CHANNEL
BABUYAN ISL.
CAGAYAN
ABRA
IBABELA
NUEVA VIZCAYA
NUEVA ECIJA
TARLAC
ZAMBALES
PANGASINAN
BATAAN
BULACAN
PAMPANGA
RIZAL
LAGUNA
CAVITE
BATANGAS
MINDORO
MARINDUQUE
TAYABAS
ALBAY
SORSOGON
CATANDUANES
MASBATE
CAMARINES NORTE
CAMARINES SUR
ANTIQUE
CAPIZ
ILOILO
NEGROS OCCIDENTAL
NEGROS ORIENTAL
CEBU
BOHOL
LEYTE
SAMAR
SURIGAO
AGUSAN
MISAMIS
LANAO
BUKIDNON
DAVAO
COTABATO
SULU
BASILAN I.
CUYO IS.
CALAMIANES
BUSUANGA
CULION I.
CHINA SEA
SULU SEA
MINDANAO SEA
CELEBES SEA
PHILIPPINE SEA
PACIFIC OCEAN
PLACER
BUCAS GRANDE I.
TAGANITO
IRON ORE RESERVATION
ADLAY
CANTILAN
Lake Mainit

FIG. 1.

Jan. 544.0	April 254.3	July 177.2	Oct. 272.1
Feb. 376.9	May 158.6	Aug. 129.8	Nov. 427.2
Mar. 353.4	June 123.2	Sept. 167.7	Dec. 619.8
			Total 3,604.2

Vegetation.—The area between the barrios of Claver and Carrascal is comparatively barren of vegetation. Extensive areas of bare red soil are common, and the stunted trees and brush are sporadic in their growth and distribution.

Jungle growth is present only in the deeply-incised erosion cuts and stream gullies. The barren areas extend to the west, back to the foot of Mt. Legaspi where they meet the timber line.

History.—The deposits were first recognized by H. F. Cameron, chief engineer for the Department of Mindanao and Sulu, in 1912. Cameron, who had had earlier experience in the Mayari district of Cuba, noticed them while sailing along the Surigao coast. The analysis of the ore samples, submitted by him to the Bureau of Science, Manila, showed that they were similar in composition to the Cuban ores. Analyses[3] of the Cuban and Surigao ore are given in Table 1.

TABLE 1.

	SiO_2.	Al_2O_3.	Cr_2O_3.	Fe_2O_3.	FeO.	NiO.	MgO.	S.	P.	H_2O comb.	Total.
Cuban[a] (Mayari)	4.16	9.00	2.90	64.48	1.18	1.69	1.50	—	—	12.26	101.17
Surigao	1.20	12.20	1.28[b]	77.71[c]	—	None	—	Tr.	Tr.	7.63	100.02

[a] Average analysis of 3 samples.
[b] 1.28 Cr_2O_3 = 0.88 Cr.
[c] 77.7 Fe_2O_3 = 54.4 Fe.

Two years after Cameron's discovery, Wallace E. Pratt, in a memorandum to Alvin J. Cox, Director of the Bureau of Science, recommended the Insular Government withdraw all lands from which the iron samples had been taken until a geological reconnaissance was made of the region. On June 25, 1914, Governor-

[3] Kemp, J. F.: The Mayari iron-ore deposits, Cuba. A. I. M. E. Trans., 51: 23, 30, 1915.

General Harrison issued Executive Order No. 63 which withdrew the area from mineral location.

During 1915, the Bureau of Science sent Pratt and Lednicky to Surigao to study the iron deposits. In their report [4] they state that the deposits cover an area of approximately 100 square kilometers, the ore mantle ranging up to about 20 meters in thickness. The iron-ores were described as clayey residual products formed by the decomposition of igneous rocks and "are similar to the laterites in origin found commonly in tropical countries." The character of the ore is described as being principally ferruginous clay containing "an abundance of small rounded pellets of hydrous iron oxides. . . ." Their analyses of the ores are given below.

Hygroscopic H_2O.	Combined H_2O.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	Cr_2O_3.	S.	P.	NiO.	Total.
13.50	6.60	1.04	10.56	66.80	0.36	1.15	Tr.	Tr.	Nil	100.01

Analyses of 31 samples, "selected as representative of a total of 183 samples" averaged 47.40 per cent metallic iron. Total iron-ore reserves in the Surigao reservation were estimated at 500,000,000 metric tons.

Upon completion of the above survey, the Bureau of Science engineers were of the opinion that the market for such ores was not available. It was felt that other known iron deposits in the Far East were in a much more favorable position for exploitation and that the Surigao ores would not be able to compete with higher grade ores on the market. Certainly the Philippine Industrial demand did not justify the opening of the deposit in 1915.

Interest in the Surigao deposit was revived in 1937, by persistent efforts to secure a lease, so the newly organized Commonwealth Bureau of Mines undertook a detailed geological study and exploration program. From October 1937 to December 1938, the iron-ores adjacent to the Surigao coast and in the in-

[4] Pratt, W. E., and Lednicky, V. E.: Iron-ore in Surigao Province. Philippine Jour. of Sci., X, Sec. A, No. 5: 335–346, 1915.

terior were under survey. During this period 1695 holes were drilled to determine the depth and nature of the ore, and over 2000 ore samples were taken and analyzed. Engineering plans were also prepared for mining 20,000,000 tons of the ore; and soundings were made in the excellent natural harbor at Dahican Bay by the United States Coast and Geodetic Survey.

PHYSIOGRAPHY.

The main topographic feature of Surigao province is the Diwata Mountain range that cuts across the southwestern corner of the government reservation in a northwesterly direction. East of the Diwata Range isolated peaks and small mountain ranges fill in the central part of Surigao province. The most conspicuous peak in the area is Mt. Legaspi with an elevation of 1170 meters. These highlands with their eastward extensions form the western border of the iron covered plateau region adjacent to the eastern Surigao coast. The plateau varies in elevation from 60 to approximately 700 meters above sea level, the major portion of the area being comparatively uniform in elevation. The plateau is made up of a series of broad flat ridges and intervening short, narrow, deeply-incised valleys that expose the varying thicknesses of the ore mantle and the general features of the underlying bed rock.

Two rivers drain the area, the Hegapit, which discharges at Taganito, and the Paniquian, which drains the eastern flank of Mt. Legaspi and empties into Carrascal Bay.

The coast line is moderately irregular and is marked by narrow beaches and steep high sea cliffs. Although the eastern coast of the government reservation is comparatively rugged, good harbors are rare between the barrios of Gigaquit and Cantilan. Dahican Bay, however, is an excellent natural harbor protected at all times during the year, Fig. 2. This bay trends generally north-south and is approximately 3 kilometers long. It varies in width from two hundred fifty meters at the south end, to approximately one kilometer at the extreme north end where it funnels into the open sea. In depth the bay varies from 6 to

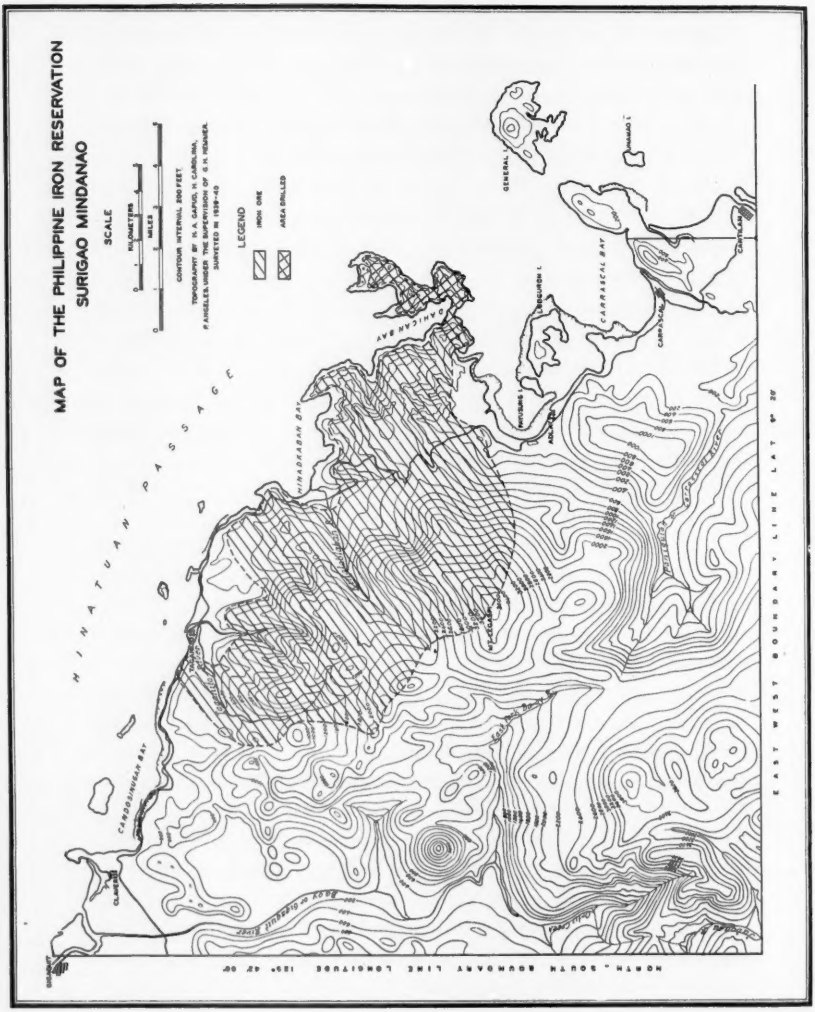
MAP OF THE PHILIPPINE IRON RESERVATION
SURIGAO MINDANAO
SCALE
KILOMETERS
MILES
CONTOUR INTERVAL 200 FEET
LEGEND
IRON ORE
AREA DRILLED
HINATUAN PASSAGE
CARRASCAL BAY
CANTILAN
NORTH - SOUTH BOUNDARY LINE LONGITUDE 126° 42' 00"
EAST WEST BOUNDARY LINE LAT 9° 30'

FIG. 2.

20 fathoms; the shallow water is found along the shores where fringing coral reefs have grown.

GENERAL GEOLOGY.

At present little is known about the general geology of eastern Surigao Province. Field studies during 1937–1938 were confined entirely to restricted areas of the iron-ore.

In general, the iron-ore forms a nearly horizontal mantle over the plateau area, adjacent to the eastern Surigao coast between the barrios of Capandan and Carrascal. The deposits extend to the west beyond Mt. Legaspi. Over the known areas the ore varies in thickness, being thin or totally absent on the steeper slopes and in the deeply-incised drainage channels. It rests upon a basement of highly-serpentinized ultra-basic rocks, which are plainly exposed along the sea coast and in the deeply eroded areas.

Near Capandan, sedimentary rocks, principally limestone and sandstones, overlie the serpentine rock. Pratt and Lednicky[5] state that the contact between the serpentine and overlying Miocene (?) sedimentaries marks the limit of the ore, and that the line of contact trends south-southeast from the barrio Capandan. These sedimentary rocks are also found at Carrascal on the southern edge of the iron deposit, and their contact with the ore passes to the west beyond Mt. Legaspi.

Many excellent vertical exposures of the altered massive base rock occur along the sea cliffs and in the erosion cuts. These rocks are highly fractured and faulted and consist of serpentine derived from peridotite. In many of the exposures of rock below the ore mantle, the light green serpentine may be observed to grade downward into a more dense, dark green to black, hard, serpentinized peridotite. Megascopic examination shows this dark rock to contain abundant partly altered phenocrysts of olivine and pyroxene. Grains of magnetite are also common in the serpentine rock, and in several areas where erosion has stripped off the iron-ore, small high grade chromite lenses are

[5] *Op. cit.*, p. 338.

FIG. 2.

exposed. Small veins of the hydrous-magnesium-nickel-silicate, garnierite, are locally found associated with the serpentines.

Petrographically, olivine and pyroxene, and their alteration products, predominate in the thin-sections of the serpentine rock. Although pseudomorphs of serpentine after amphibole were observed in some instances, they are rather rare. The presence of these minerals suggests that the original rocks, before alteration to serpentine, were principally dunites and rocks of the peridotite family. The alteration in mass of the dunites and peridotites to serpentine-rock probably took place during their late stages of consolidation and cooling, and as a direct consequence of hydrothermal solutions acting upon them.[6] However, since the formation of the serpentine from the original basic rocks, atmospheric weathering has been responsible for an enormous amount of alteration of the serpentine rock; the end product of such weathering in this case being the overlying mantle of lateritic iron ore.

CHARACTER OF THE IRON-ORE.

The ore blanket varies in depth from nothing to as much as 30 meters, the average depth (shown by drilling) on Dahican Peninsula (Fig. 2) being approximately 6 meters. Locally, erosion has stripped off the iron-ore to the serpentine rock, affording excellent opportunities for the study of the thickness and physical nature of the ore and also the ore base-rock contacts. The ore stands as vertical walls in the sides of the erosion cuts (Fig. 3), and in deep exploration pits that were dug more than three years ago, the sides have remained intact and still show the original pick marks.

On first examination the contact between the ore and the base rock is sharp (Fig. 4), but on closer examination the serpentine appears to grade upward into a narrow greenish-yellow transition

[6] For a detailed discussion of this subject see, Bonney, T. G.: On the serpentine and associated rocks of the Lizard district. Quart. Jour. Geol. Soc., 33: 884, 1877; On antigorite and antigorite-serpentine. Quart. Jour. Geol. Soc., 64: 152, 1908. Graham, R. P. D.: Origin of massive serpentine and chrysotile-asbestos, Black Lake-Thetford Area, Quebec. Econ. Geol., 12: 154, 1917. Benson, W. N.: The origin of serpentine, a historical and comparative study. Am. Jour. Sci., 196: 693, 1918.

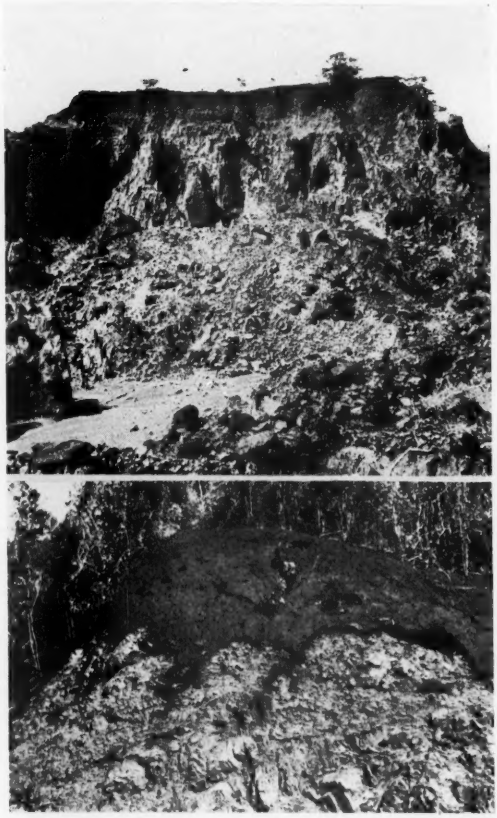

FIG. 3. Erosion face exposing 11 meters of ore, Dahican Peninsula. The cliff shows the red zone, dark band at top, grading downward into lower light yellow zone.

FIG. 4. Outcrop showing a sharp contact between the serpentine and ore. Serpentine fragments can be seen in ore just above the contact. (Height of outcrop 7 meters.)

zone of soft, compact, moist, earthy material composed of hydrous iron oxides and partly decomposed remnants of serpentine. The included serpentine fragments give this zone its greenish tint. This zone grades upward into a fine-grained yellow ore of clay-like consistency that has a high porosity and moisture content.

Near the surface, the yellow ore grades into a more coarsely-textured deep-red zone, consisting of small hard hematite and magnetite pellets dispersed through a matrix of soft granular iron oxide and bauxite. The magnetite and hematite pellets or "shot," range up to 1 cm. in diameter, increase in quantity and size near the surface, and are often found cemented into surficial crusts and large boulders (Fig. 5). Locally, on the surface of

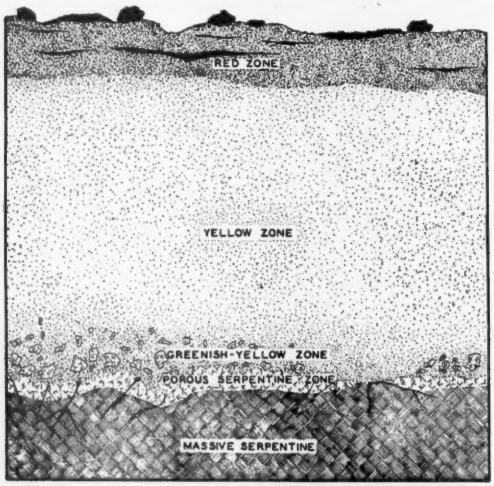

FIG. 5. Idealized vertical section showing iron-ore zones and serpentinized rock.

the ore and below it, crusts and continuous sheets of hard brown cellular limonite occur.

Limonite predominates in the ore and is associated with varying amounts of hematite and subordinate amounts of magnetite.

The average analyses of 2000 samples, from the drilled area and from widely scattered erosion faces, show the ore to contain 47.77 per cent metallic iron. In general, the iron tends to decrease slightly near the surface but remains rather uniform in grade downward, in some instances increasing in percentage toward the bottom of the ore. Hygroscopic water averaged 26.77 per cent, combined water 13.61 per cent. Phosphorus averaged .03 per cent, silica 1.33 per cent, alumina 7.93 per cent, chromium 4.19 per cent, sulphur .17 per cent, and nickel .78 per cent.[7]

The most common impurity in the Surigao ore is bauxite which is often found in small lumps on the surface. As a rule these lumps are light gray, hard and porous, and commonly show narrow red banding. Kaolin is found in subordinate amount.

ORIGIN OF THE SURIGAO IRON-ORE.

The theory of lateritic origin of the Surigao iron-ores is based upon field evidence supported by petrographic, mineralogical, and chemical data. Pratt and Lednicky[8] in their discussion of the geology of the Surigao deposits, as already mentioned, state, "the iron-ores are clayey residual products from the decomposition of igneous rocks. They are similar to the laterites in origin found commonly in tropical countries." Although these early investigators thus recognized the ores to be lateritic in origin and to have been formed by weathering of the serpentine rock, they gave no detailed information on the process involving their formation.

The formation of lateritic iron-ore from the serpentine rock is here considered from four aspects: (*a*) interpretation of field occurrences of the ores, (*b*) petrographic evidence of alteration, (*c*) mineralogical change from serpentine rock to lateritic iron-ore expressed in terms of weight, and (*d*) progressive chemical changes that occur during the development of the iron-ore. In 1911 and 1915, Leith and Mead[9] published data on the origin of

[7] Analyses by H. C. Witt, Elizalde Co., Manila.

[8] *Op. cit.*, p. 338.

[9] Leith, C. K., and Mead, W. J.: Origin of the iron-ores of Central and Northeastern Cuba. A. I. M. E. Trans., XLII: 90–102, 1911; Additional data on origin of lateritic iron-ores of Eastern Cuba. A. I. M. E. Trans., LII: 75–78, 1916.

the lateritic iron-ores of Cuba. By quantitative measurements of the lateritic alterations they showed conclusively that the Cuban ores were derived from the underlying serpentine rock. In order to show the remarkable similarities between the Surigao and Cuban laterites, the quantitative methods of measurement, used by the above investigators, have been followed as closely as possible.

Interpretation of the Field Occurrence of the Ores.—The serpentine shows evidence of alteration from a dark green massive rock upward into a lighter colored and highly porous serpentine zone near the iron-ore contact. The porous zone is, as a rule, rarely more than one-half meter in thickness. The pores are partly filled with soft hydrous iron oxides. Progressing upward, the porous horizon grades into an ore zone of greenish tint, the color being due to included small fragments of serpentine. Gradually, this zone merges upward into the much thicker yellow ore. Such a gradation from the serpentine rock into the iron-ore can be observed in numerous erosion cuts where the bed rock and iron-ore contacts are exposed, Fig. 5.

The gradation described above is interpreted as due to the leaching of the serpentine rock by atmospheric waters. The highly fractured serpentine offers excellent opportunities for ground waters to alter the rock by removing its more soluble constituents such as magnesia, and silica. As the alteration progresses and some of the soluble constituents are removed in solution, the serpentine becomes more porous and the insoluble components, or the end products of weathering, are left in the voids and cracks in the serpentine. Further action of percolating waters gradually reduces the serpentine remaining in the porous zone and the volume of iron oxides increases proportionally, thus giving rise to the ore zone, which is composed mostly of iron minerals and isolated fragments of green serpentine. Eventually these fragments are broken down, the greenish ore zone disappears, and the iron-ore takes on a yellow color.

The porous zone in the serpentine and the greenish-yellow ore zone above it rarely exceed one meter in thickness. Commonly, neither zone is visible, and the iron ore appears to rest directly

upon the massive serpentine. In both instances, however, the contact has an extremely sharp appearance; the sharpness being accentuated by color contrasts. The porous zone has a low permeability, but the greenish-yellow ore zone is highly permeable. As a result springs and seepages along the base rock contact are very common, the meteoric waters having percolated downward through the iron-ore until they strike the less permeable porous serpentine and flow out over it. The high permeability of the ore lends to the rapidity of alteration of the serpentine fragments in it, and their breakdown into iron hydroxides takes place. The predominance of these iron minerals in the greenish-yellow zone gives the contact between the ore and serpentine its sharp appearance.

Petrographic Evidence of Alteration.—It has been mentioned in the preceding pages that the serpentine rock tends to change in physical appearance with depth, these changes being noticeable in the deeper erosion cuts. Microscopic studies of specimens taken at closely spaced vertical intervals over some of these exposures show unmistakably that there is a gradational change from fresh serpentine rock to the iron-ore above. In other words, the degree of alteration of the original mineral constituents of the serpentine rock increases upward to the iron-ore contact. Such progressive destruction of the country rock is ascribed to the action of percolating ground waters.

In the fresh serpentine rock, near the base of the outcrops, olivine and pyroxene remnants make up a high percentage of the rock, and their alteration to antigorite and bastite is pronounced. The olivine is shattered, due to increase in volume accompanying serpentinization, and the interstitial material between fragments is composed of antigorite containing small amounts of magnetite, Fig. 6.

Large crystals of pyroxene (enstatite) are commonly partly altered to bastite, which is composed of small fibers that do not cross the cracks in the mineral. Other crystals of the mineral are completely transformed to bastite-serpentine in which the fibrous structure still shows the original outline of the pyroxene.

Although no amphibole was found in the thin sections its presence may be inferred from the peculiar lattice structure observed in Fig. 8.

Progressing upward from the base of the outcrop there follows a marked change in the degree of alteration of the olivine and

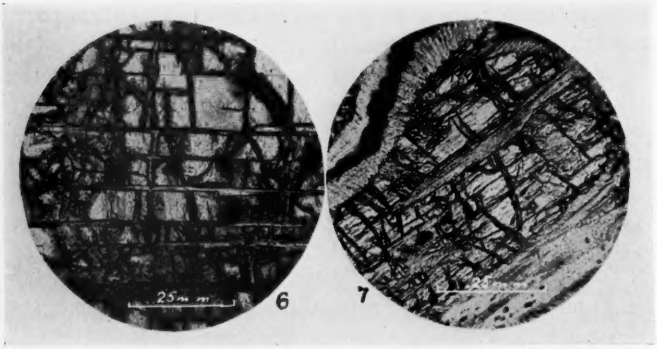

FIG. 6. Olivine (light-gray) shattered into angular fragments by serpentinization and volume increase. Opposite sides of pieces still match and would fit together if the interstitial antigorite were removed. Alteration to antigorite can be seen along the fractures or cracks, leading to fibration in lower area of picture; the black areas are limonite and magnetite. The original rock was probably a dunite.

FIG. 7. Large olivine crystal (fractured mineral) of which the matrix is serpentine (antigorite) with subordinate secondary magnetite (rounded black areas). This shows the method of alteration of olivine to serpentine; alteration starts in cracks and peripheries and leads to fibration, and at the same time separation of iron oxides (dark band in upper left of picture limonite and magnetite). The fibres of serpentine mostly stand roughly perpendicular to the boundaries of the olivine remnants.

pyroxene; the relics of these minerals are more altered, less abundant, and show more extensive serpentinization (Fig. 7). As the surface is approached, the destructive effects of the ground waters on the serpentine rock become even more pronounced. From the thin sections, it is evident that these waters have gained access to the interior of the olivine relics by means of cracks and have al-

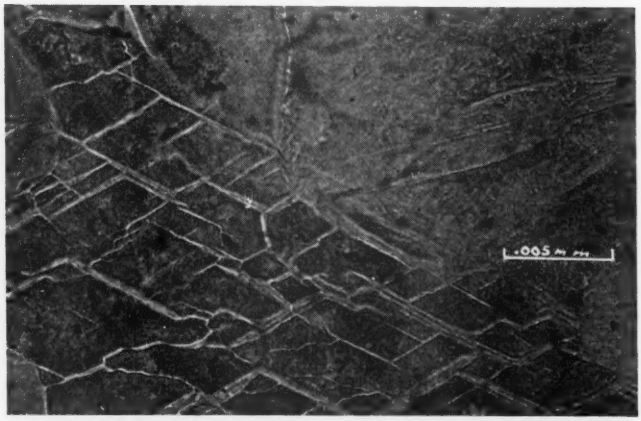

FIG. 8. Serpentine after amphibole (?). Positions of light gray bands (colorless in section) gives lattice structure; central areas or mesh are isotropic serpentine, transparent green in section.

tered this mineral. Breakdown of the olivine is accompanied by the separation of iron oxides (ferric oxide, hydrated ferric oxide, or magnetite) which have been deposited along the cracks (Figs. 9, 10).

The olivine becomes less abundant upward and the iron minerals, limonite and magnetite, increase in quantity at the expense of the olivine (Fig. 11). A few inches below the iron-ore contact, the country rock is composed entirely of fibrous serpentine and iron oxides (Figs. 12, 13). Sections of the serpentine from this zone commonly show a peculiar "mesh structure," which has been produced by the alteration of olivine; the mesh consists of iron oxides (derived from the olivine) and the net outlines are made up of antigorite (Fig. 14).

Although the petrographic evidence points especially to the destruction of the pyroxene and olivine, the alteration continued with the destruction of the serpentine minerals, antigorite and bastite. Percolating ground waters attacked these minerals, decomposed them in situ, and the soluble chemical constituents such

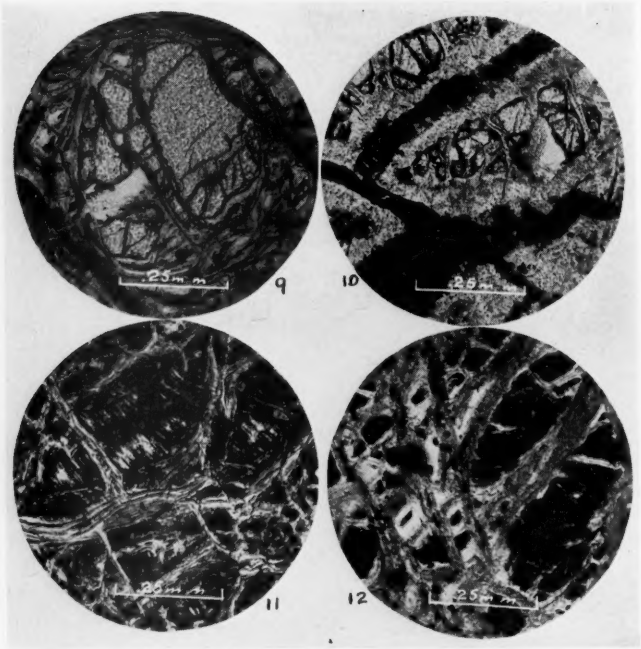

FIG. 9. Progressive serpentinization of olivine (shagreen surface); the fibrous matrix is antigorite with black areas of iron oxides. The section shows a marked increase of antigorite and iron oxides at the expense of primary olivine.

FIG. 10. Serpentine showing more advanced stage in alteration of olivine relics (shagreen surfaces) surrounded by antigorite zones separated by black bands of limonite and magnetite. Grey zones around the olivine show the probable extensions of the mineral before it became altered.

FIG. 11. More advanced stage of alteration of the olivine (Antigorite-fibrous grey mineral). Olivine (jagged areas surrounded by black iron oxides) has almost completely disappeared.

FIG. 12. Serpentine showing iron oxides (black) and serpentine minerals (grey); the black areas were originally occupied by olivine remnants. The rock specimen was taken two feet below iron-ore contact.

as silica and magnesia were carried out in solution. By this process through long periods of time, great quantities of soluble material have been removed, and the insoluble constituents of the serpentine rock, such as alumina, chromium and iron, have accumulated to form the lateritic deposits.

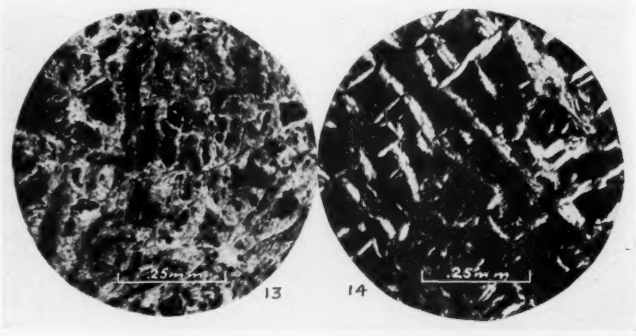

FIG. 13. Serpentine near iron-ore contact. Serpentine (grey) and limonite (black) showing the serpentine rock in an advanced stage of alteration to iron-ore. As the alteration progresses the soluble constituents of the serpentine are removed in solution and the more insoluble material (alumina, chromium, and iron oxides) remain.

FIG. 14. Serpentine under crossed nicols showing the "mesh structure," produced by alteration of olivine in situ. The mesh consists of limonite (black) and antigorite (grey). The specimen was taken at iron-ore contact.

Mineralogical Change from Serpentine Rock to Lateritic Iron-ore Expressed in Terms of Weight.—Mineralogical composition of the ores and bed rock has been calculated from the analysis (Fig. 15) of 58 samples taken at 1 foot intervals from a vertical exposure of ore and bed rock. The changes in mineralogy from the serpentine rock through the iron-ore to the surface, calculated from the given analyses, are expressed in terms of weight, based on the assumption that alumina has remained constant throughout the alteration (Fig. 16). The iron has been recast into the minerals limonite and hematite; this does not necessarily mean that

CHEMICAL ANALYSES SHOWING ALTERATION OF SERPENTINE BED ROCK TO IRON ORE #

Depth in Feet	Percentage										TOTAL
	SiO_2	Al_2O_3	Fe_2O_3	Fe	MgO	Cr	Ni-Co	P	S	Comb. H_2O	
0-1	1.42	12.00	68.01	47.57	0.08	2.71	0.71	0.039	0.17	13.2	98.339
1-2	1.36	12.54	68.77	48.10	0.65	2.70	0.74	0.034	0.30	12.8	99.294
2-3	1.28	10.84	69.60	48.68	0.07	2.71	0.78	0.034	0.28	12.4	97.994
3-4	1.04	9.68	70.76	49.49	0.09	3.10	0.88	0.028	0.28	12.2	98.058
4-5	1.50	8.48	71.19	49.79	0.04	2.71	0.83	0.028	0.26	12.2	97.238
5-6	1.48	7.60	72.49	50.70	0.06	2.85	0.80	0.029	0.24	11.9	97.449
6-7	1.42	7.56	72.35	50.60	0.63	2.58	0.77	0.039	0.19	12.4	97.168
7-8	1.72	7.20	72.92	51.00	0.02	2.85	0.93	0.025	0.21	11.6	97.475
8-9	1.30	6.68	72.63	50.80	0.09	3.75	0.91	0.033	0.27	12.3	97.965
9-10	1.42	6.68	73.93	51.71	0.04	3.62	0.93	0.022	0.20	12.0	98.842
10-11	0.60	6.00	73.93	51.71	0.07	2.84	0.81	0.028	0.15	11.6	96.028
11-12	0.52	5.80	73.65	51.51	0.04	3.48	0.85	0.031	0.15	11.9	96.421
12-13	0.50	7.36	74.65	52.21	0.02	2.67	0.69	0.031	0.13	11.5	97.551
13-14	0.54	6.34	74.93	52.41	0.05	2.84	0.85	0.033	0.16	11.1	96.843
14-15	0.46	5.58	74.07	51.81	0.01	3.42	1.36	0.034	0.16	11.9	96.994
15-16	0.88	5.96	73.65	51.51	0.02	3.65	1.35	0.042	0.16	12.1	97.812
16-17	1.38	5.70	72.35	50.60	0.02	3.67	1.14	0.045	0.14	12.2	96.645
17-18	1.82	5.24	71.76	50.19	0.01	3.61	1.27	0.028	0.15	12.5	96.388
18-19	0.46	6.90	67.43	47.16	0.04	3.59	1.46	0.039	0.16	14.2	94.279
19-20	0.42	5.50	71.76	50.19	0.02	3.42	1.24	0.039	0.15	13.1	95.649
20-21	0.52	6.58	72.35	50.60	0.02	2.20	1.40	0.028	0.17	12.8	96.068
21-22	0.52	6.82	68.58	47.97	0.02	3.36	1.82	0.036	0.18	13.2	94.536
22-23	0.64	8.08	64.26	44.94	0.02	3.55	1.79	0.036	0.16	14.2	92.736
23-24	0.44	6.70	70.17	49.08	0.02	3.55	1.20	0.042	0.17	12.7	94.992
24-25	0.78	5.28	72.35	50.60	0.02	2.97	0.98	0.039	0.16	11.8	94.379
25-26	0.46	8.38	72.49	50.70	0.03	2.36	0.95	0.020	0.17	11.8	96.660
26-27	0.94	7.50	73.79	51.61	0.02	2.97	0.66	0.031	0.16	10.4	96.471
27-28	0.92	5.90	74.08	51.81	0.01	2.39	1.12	0.036	0.16	10.7	95.316
28-29	0.76	6.90	73.20	51.20	0.04	2.46	1.00	0.025	0.18	11.7	96.265
29-30	0.82	7.00	72.63	50.80	0.04	2.59	0.91	0.028	0.18	11.8	95.998
30-31	0.82	6.58	72.35	50.60	0.05	3.37	0.77	0.028	0.17	11.6	95.518
31-32	0.82	6.92	73.35	51.30	0.05	2.64	0.82	0.058	0.17	12.1	96.628
32-33	0.68	7.14	74.08	51.81	0.05	2.05	0.93	0.025	0.13	11.3	96.385
33-34	0.72	6.54	73.06	51.10	0.05	2.05	0.76	0.036	0.14	12.3	95.656
34-35	0.72	5.76	73.35	51.30	0.04	3.63	0.86	0.022	0.14	11.4	95.922
35-36	0.82	7.02	72.20	50.50	0.04	3.69	0.70	0.025	0.15	12.0	96.345
36-37	0.78	7.76	72.05	50.39	0.04	3.76	0.75	0.025	0.16	11.9	97.225
37-38	1.04	6.66	73.79	51.61	0.04	1.98	0.70	0.023	0.15	12.1	96.483
38-39	0.48	5.08	73.65	51.51	0.05	4.36	0.62	0.034	0.10	12.1	96.474
39-40	0.82	5.88	72.63	50.80	0.04	4.36	0.59	0.039	0.15	11.6	95.909
40-41	1.38	5.68	72.92	51.00	0.04	3.59	1.18	0.050	0.29	11.9	97.030
41-42	1.16	4.86	72.78	50.90	0.04	4.36	0.98	0.042	0.22	10.3	95.120
42-43	1.02	5.04	72.78	50.90	0.04	4.06	0.97	0.034	0.21	11.1	95.254
43-44	0.88	4.76	72.92	51.00	0.04	2.93	1.00	0.039	0.21	12.1	94.879
44-45	0.82	4.84	74.93	52.41	0.04	3.33	1.18	0.053	0.20	11.6	96.993
45-46	1.06	10.02	71.33	49.89	0.04	3.20	0.97	0.039	0.20	11.5	98.359
46-47	1.74	8.42	69.99	48.88	0.04	3.46	1.15	0.042	0.19	10.9	95.832
47-48	0.42	8.58	70.46	49.28	0.04	2.07	1.17	0.039	0.26	13.2	96.239
48-49	0.64	6.14	71.62	50.09	0.04	4.24	1.19	0.053	0.22	12.2	96.333
49-50	0.42	6.22	71.90	50.29	0.04	4.13	1.18	0.047	0.21	11.1	95.247
50-51	1.16	4.06	73.93	51.71	0.05	3.62	1.10	0.039	0.20	12.6	96.659
51-52	1.22	7.46	72.20	50.50	0.04	2.73	1.45	0.033	0.18	12.3	97.613
52-53	1.30	6.16	73.06	51.10	0.04	2.73	1.22	0.050	0.14	12.0	96.700
53-54	0.90	5.22	73.06	51.10	0.05	2.93	1.46	0.047	0.18	12.6	96.447
54-55	0.80	5.66	72.35	50.60	0.05	3.06	1.41	0.025	0.18	12.4	95.935
55-56	0.56	6.40	71.05	49.69	0.06	2.73	1.79	0.028	0.14	12.6	95.358
56-57	58.00	2.78	114.87	10.40	6.47	.53	1.03	0.053	0.16	13.2	97.093
57-58	37.70	1.90	111.33	7.93	34.75	.37	0.51	10.013	0.11	12.85	99.533

Analyses by H. C. Witt, Elizalde Co., Manila

FIG. 15.

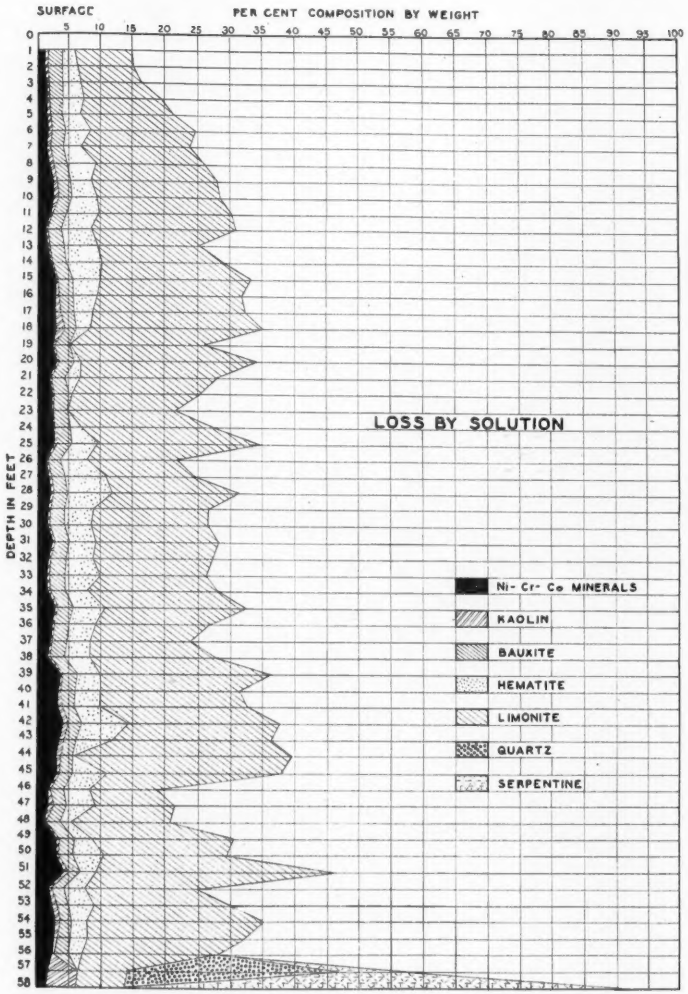

FIG. 16. Graph showing mineralogical changes in the alteration of serpentine to lateritic iron-ore.

other hydrous iron oxides are not present in the ore. The mineral magnetite has been included in hematite. The base rock is considered to consist mainly of serpentine. Serpentine is almost completely lost by the process of weathering with the accompanying development of limonite and a marked increase in porosity. Excess silica, appearing as quartz in the accompanying graph, is apparent at the serpentine contact. All the silica in the iron-ore is believed to have been derived from the decomposition of the serpentine, and its excess near the contact is marked in part, by the presence of small, irregularly shaped, cherty flakes. Waters, seeping downward through the iron-ore, may carry some silica in solution and deposit it near the bed rock in the cherty form. The ore nearest to the serpentine rock shows that the serpentine has been almost completely destroyed. Hematite and a subordinate amount of magnetite appear with the limonite and in general increase upward. The hematite and magnetite have been formed by the de-hydration and de-oxidation of the limonite. Kaolin is found in very small amount and tends to decrease upward, whereas bauxite occurs in larger amounts and tends to increase toward the surface. Chromium, nickel, and cobalt are found through all phases of alteration of the serpentine rock and ore.

Progressive Chemical Changes Taking Place During the Development of Iron Ore.—The progressive chemical changes that have taken place during the development of the Surigao ore are shown graphically, Fig. 17. This graph is based on the analyses given in Fig. 15 and it shows the progressive gains and losses of constituents during alteration.

Using the "straight line diagram," [10] successive steps in the alteration of the serpentine rock to iron ore can be easily demonstrated. Each analysis in Fig. 15 has been compared with the analysis of the unaltered serpentine rock. Individual points on the horizontal scale, for a given constituent, indicate the number of grams of altered rock or ore necessary to contain the same

[10] Leith, C. K., and Mead, W. J.: Metamorphic Geology, pp. 287–289, Henry Holt and Co., New York, 1915.

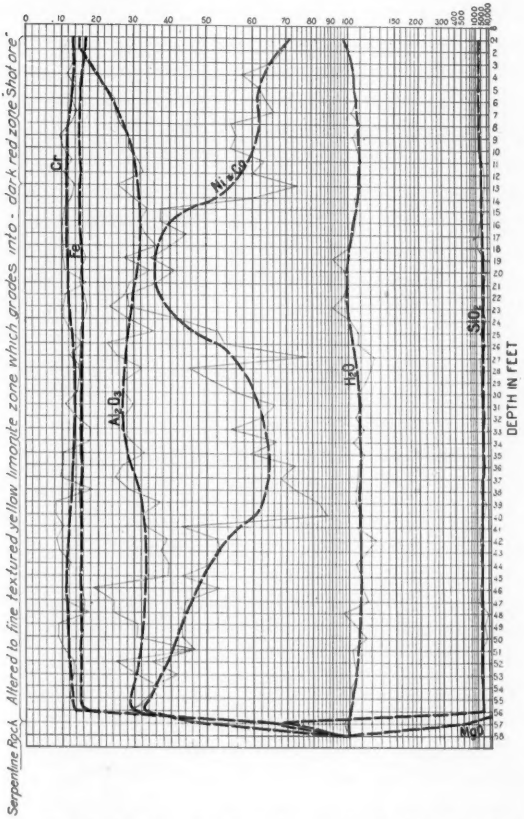

FIG. 17. Graph showing chemical changes in the lateritic alteration of serpentine producing the Surigao iron-ore.

amount of the given constituent as 100 grams of unaltered serpentine bed rock. For instance, 16 grams of ore, at the surface, are required to contain the same amount of alumina as 100 grams of serpentine rock, and assuming the alumina to have remained constant, 100 grams of serpentine rock produce 16 grams of ore at the surface. If it is assumed that any one constituent has

remained constant during the alteration, all constituents lying to the left of that constituent's line or point have been relatively increased and those to the right have been relatively lost.

Progressing upward from the unaltered serpentine rock, magnesia is almost completely lost. The silica curve shows a slight increase within a narrow zone immediately above the bed rock, and then turns sharply to the right, showing a maximum loss 2 feet above the serpentine rock. From this point to the surface it remains rather constant. Alumina, chromium, iron, nickel, and cobalt increase rapidly in percentage with the loss of magnesia and silica. Chromium and iron reach their constant maximum percentages at the depth where silica reaches its minimum percentage. At a depth of 18 feet the alumina curve turns to the left, showing an increased rate of concentration. The iron curve turns slightly to the right near the surface, showing a slight decrease. The increase of alumina as compared with iron is probably due to the solution of the iron in the upper portion of the ore and its transportation and secondary concentration downward. Chromium has remained rather uniform throughout the process. Chromium, iron, and nickel-cobalt are lost relative to alumina, the loss being most conspicuous in the lower zones and at about the same depth from the surface at which the alumina shows an increased rate of concentration. The marked loss of nickel and cobalt near the surface and its marked increase in different zones at depth suggest that it has been secondarily concentrated downward during the formation of the ores. The rapid increase of nickel near the serpentine rock is due to the presence of abundant small veins of garnierite in the partly altered and fresh serpentine rock.

COMPARISON OF SURIGAO AND CUBAN LATERITIC IRON ORES.

The Surigao and Cuban laterites have been formed under tropical climatic conditions and are almost identical in physical character, mineralogy, and chemical composition. Both deposits have been formed in situ, appear as surface mantles of varying thickness, and are associated with a serpentine rock from which they have been derived by katamorphic processes. In vertical

section the ores of both localities show definite gradations from the green serpentine rock below to a greenish-yellow and a yellow earthy-limonite zone of clay-like consistency above. This in turn grades upward into a brick-red zone that is mealy or granular near the surface. So called "shot-ore" or small rounded pellets of hematite and magnetite appear to be concentrated in the upper red zone and are commonly found in cemented sheets (known as planchas in Cuba) on and near the surface. Mineralogically, limonite and hematite, with subordinate amounts of magnetite, predominate in the ores, and bauxite, kaolin, quartz, nickel, cobalt, and chromium minerals are found in lesser amounts. All these minerals occur in approximately the same proportions in the Surigao and Cuban deposits.

Progressive chemical changes that have taken place during the development of the Cuban and Surigao lateritic ores result in gains and losses of different constituents. During the alteration of the serpentine rock magnesia and silica have been rapidly lost, the magnesia almost completely disappearing a few feet above the serpentine rock, whereas the silica is reduced to a minimum a few feet above the base rock and from this point to the surface remains essentially constant. Chromium, iron, and alumina rapidly increase in percentage with the loss of silica and magnesia. In both deposits the iron content reaches a maximum at approximately the same depth at which silica reaches its minimum percentage. Alumina shows an increased rate of concentration near the surface in both deposits, whereas the iron and chromium tend to decrease in amount. However, there appears to be more of a marked loss in iron and chromium, in reference to alumina, in the surface zone of the Cuban deposits than in the Surigao ores. Nickel and cobalt are lost relative to iron, chromium, and alumina, the loss being more pronounced at about the depths where the alumina content is increased. Percentage of combined water remains rather constant upwards through the ores in both deposits. Average chemical analyses of Surigao and Cuban iron-ores and serpentine rock, are given in Table 2.

TABLE 2.

CHEMICAL ANALYSES OF CUBAN AND SURIGAO SERPENTINE AND IRON-ORE.

	Cuba.						Surigao.				
	Serpentine.			Iron-ore.			Serpentine-rock.			Iron-ore.	
	A.	*B.*	*C.*	*D.*	*E.*	*F.*	*G.*	*H.*	*I.*	*J.*	*K.*
SiO_2	37.29	37.28	39.80	1.71	4.16	3.63	33.18	37.40	39.76	1.04	1.33
Al_2O_3	1.33	2.45	1.39	11.60	9.00	11.77	0.44	1.16	1.11	10.56	7.93
Fe_2O_3	—	5.14	—	66.90	64.48	64.72	3.73	6.75	2.40	66.80	—
Fe	—	—	—	—	—	45.26	—	—	—	—	47.77
FeO	8.55	5.14	9.10	—	1.18	—	2.60	0.72	4.45	0.36	—
CaO	0.29	none				—	0.28	1.46	0.09	—	—
MgO	36.53	34.59	33.69	2.38	1.50	—	40.91	32.87	39.82	—	—
K_2O	trace	—	—			—	0.12	00.08	0.13	—	—
Na_2O	0.39	—	—	—	—	—	0.27	0.15	0.10	—	—
TiO_2		—	—	0.14	—	—	nil	nil	nil	—	—
Cr_2O_3	0.28	1.68	(Cr) 0.20	2.65	2.90	Ni	0.51	0.76	0.18	1.15	4.19
NiO		0.30	(Ni-Co) 0.30	0.60	1.69	Co 1.91 Cr	0.13	0.21	0.18	none	(Ni) .78
P_2O_5	0.07	0.013	—	0.07	—	(P) .009	nil	nil	nil	(P) tr.	(P) .03
MnO	—	—	—	0.80	—	—	0.23	0.32	0.44	—	—
S	—	—	—	—	—	—	nil	0.04	trace	trace	.17
Cl	—	—	—	—	—	—	0.02	0.03	trace	—	—
H_2O Comb.	15.27	12.80	—	13.15	12.26	12.30	—	—	—	6.60	13.61
H_2O Absorb.	—	0.91	—	—	—	—	—	—	—	13.50	26.77
Ignition loss	—	—	—	—	—	—	17.10	17.60	10.90	—	—
Total	100.00	100.303	84.21	100.00	101.17	94.339	99.52	99.55	99.56	100.01	102.58

A, D. Serpentine and iron ore, Moa Bay, Cuba. Described by C. M. Wield in Trans. A. I. M. E., Vol. XL, p. 304, 1909.

B, E. Woodfred Serpentine and Mayari iron-ore, Cuba. (Average of 3 Samples.) Described by J. F. Kemp in Trans. A. I. M. E., Vol. LI, p. 19, 23, 1915. Analysis by T. C. Kraemer.

C. Serpentine, Moa, Cuba. Described by J. S. Cox in Trans. A. I. M. E., Vol. XLII, p. 75, 1911.

F. Iron-ore Mayari and Moa. (Average from table.) Described by C. W. Hayes in Trans. A. I. M. E., Vol. XLII, p. 113, 1911.

G, H, I. Serpentine, Dahican Bay, Surigao. Analysis by J. Roco.

J. Iron-ore, Surigao. Described by W. E. Pratt and V. E. Lednicky in Phil. Jour. Sci., Vol. X, Sec. A, No. 5, p. 340, 1915. Analysis by Francisco Peña.

K. Iron-ore, Surigao. Average of 2000 samples. Analysis by H. C. Witt.

SUMMARY.

The lateritic iron-ores of Surigao Province, Mindanao, occur as surficial mantles covering a plateau-like area. The ore varies in thickness from nothing to as much as 30 meters, and is underlain by serpentinized dunites and peridotites. In well exposed sections of serpentine rock and iron-ore, the serpentine rock grades upward from a dark green, massive, highly fractured rock into a thin porous zone high in iron. Progressing upward the porous zone grades into a thin greenish-yellow ore horizon which is

overlain by a thick zone of fine textured yellow ore. This yellow zone is, in turn, capped by a comparatively thin brick-red, more coarsely textured ore zone composed of limonite, hematite, "shot ore," magnetite, and cemented sheets of these materials at and near the surface. Analyses of 2000 samples taken from the area studied, show the ore to be rather uniform in grade. Metallic iron averages 47.77 per cent; alumina 7.93 per cent; chromium 4.19 per cent; nickel-cobalt .78 per cent; silica 1.33 per cent; phosphorus .03 per cent; sulphur .17 per cent; hygroscopic water 26.77 per cent; and combined water 13.61 per cent.

The iron-ores are residual in origin, having been formed in situ by the subaerial decomposition of the serpentine rock. Samples taken at uniform intervals from a vertical section of serpentine rock and iron-ore were analysed and studied in order to show the changes that have taken place during the formation of the ore from the serpentine rock. Petrographic examination of the country rock reveals a destruction of olivine, pyroxene, and serpentine minerals with accompanying formation of iron oxides. Mineralogical composition of the ores and serpentine rock, recast from the analyses, show serpentine, quartz, limonite, hematite, (magnetite), kaolin, bauxite, and chrome, nickel, and cobalt to be present in varying percentages. Graphic representation of progressive chemical changes that have occurred during the formation of the iron-ore indicate rapid losses of the more soluble constituents like magnesia and silica, and gains of the less soluble components such as alumina, iron, chromium, nickel and cobalt.

The Surigao and Cuban laterites are very similar in physical character, mineralogy, and chemical composition, both having been formed by the katamorphic alteration of serpentine.

GEOLOGICAL SURVEY DIVISION,
BUREAU OF MINES, MANILA, P. I.,
June 15, 1940.

A MICROSCOPIC STUDY OF SOME ORES OF THE LUPA GOLDFIELD, TANGANYIKA TERRITORY, EAST AFRICA.

DAVID GALLAGHER.

ABSTRACT.

Detailed descriptions are given of the altaite-bearing gold ore of the Saza mine, and the ore of Danny Maher's mine, which contains chalcopyrite with intergrowths of cubanite indicating high temperature deposition, and abundant magnetite later than the sulphides. This is attributed to sulphur deficiency of the ore-forming solutions, and the ferrous nature of the environment. The payability of these ores is believed to be significantly related to the end-temperature of deposition, as indicated by the mineralogy. The surprising lack of oxidation and supergene processes is attributed to physical impermeability, aided in part by the peculiar chemistry of the groundwater.

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INTRODUCTION.

THE ores of the Lupa Goldfield, in Tanganyika Territory, East Africa, are relatively simple, but the reflecting microscope reveals several unsuspected features. It is the purpose of this paper to present this microscopic evidence to supplement the general description of the ores and the geology given in a previous paper.[1] The data have been derived from thin sections and polished speci-

[1] Gallagher, D. A preliminary account of the geology of a portion of the Lupa Goldfield. ECON. GEOL. 34: 243–267, 1939.

mens of the ores collected during 1935–37 in the western part of the Lupa Goldfield, chiefly from the Saza Mine.

It is a pleasure to express my gratitude for the award of the Samuel Franklin Emmons Memorial Fellowship, which made possible the study, of which this paper is a portion, and to Yale University for the hospitality and facilities provided. I wish particularly to thank Professor Alan Bateman for his guidance and critical reading of the manuscript.

GEOLOGIC SETTING.

Reference may be made to my previous paper [1] and to the work of D. R. Grantham [2] for more detailed descriptions of the general geology, although it is now known that the classification of the rocks as there presented can be simplified.[3] In briefest summary, the oldest rocks of the region are quartz-sericite schists and metadiorites that were invaded by a complex of mutually interrelated, abyssal rocks that range in composition from cortlandtite, spessartite, and pyroxene hornblendite, through diorites, quartz diorites, and granodiorites, to granites and trondhjemite, the more acidic members being the most abundant. This Lupa Suite, as I have proposed to call it,[3] is abnormal and owes its diversity to the different degrees of metasomatic microclinization and hornblendization that occurred from place to place. At a later period a small batholith of Saza granodiorite intruded the southern portion of the area, and still later the entire region was squirted full and soaked through with alaskite. The gold-quartz vein mineralization has been attributed [1] to this albite alaskite invasion, a genetic relationship that is of common occurrence throughout the world.[4] All of these events are believed to have occurred in the pre-Cambrian, or at least pre-Bukoba,[5] by the Tanganyika Geological

[2] Grantham, D. R. Lupa Goldfield. Tanganyika Geol. Surv., Bull. 3; pp. 34, 1932.

[3] Gallagher, D. Petrography of the Lupa Suite. Manuscript in preparation.

[4] Gallagher, D. Albite and gold. ECON. GEOL. 35: 698–736, 1940.

[5] The Bukoba is "Pre-Devonian and probably Paleozoic," Teale, E. O. Tanganyika Geol. Surv., Bull. 6, 1936.

Survey. The region was invaded, probably at a much later date, by a swarm of dolerite dikes.

The long geomorphic history of this ancient terrain, that has been jostled about in the incomparable Rift Valley faulting, must ipso facto be complex, but the present surface is one of mature topography, with numerous small, intermittent streams, intricately adjusted to lithology, that have very recently undergone rejuvenation.

GENERAL CHARACTER OF THE VEINS.

The general character of the veins has been described in some detail in a previous paper [1] and may be summarized briefly. They are of the massive type characteristic of deep zone deposits, and closely resemble the numerous, well known, gold-quartz veins of this type that occur throughout the world. They are composed almost entirely of quartz, and the other minerals exist as little more than traces. Chlorite, sericite, carbonates, tourmaline, pyrite, chalcopyrite, galena, molybdenite, and gold have been identified megascopically; but the combination and distribution of these minerals differs from vein to vein, and within the individual veins.

Gangue.—A number of varieties of quartz are present, including white bull-quartz, glassy quartz, porcelain-like quartz, smoky quartz, and blue quartz. The bull-quartz veins are barren, but the veins showing quartz that ranges from clear milk white to dark blue, and from nearly transparent to barely translucent are mineralized. Commonly, the white quartz and the blue are intermingled giving rise to a very irregular mottling, or to a bacon-like, streaked pattern.

A longitudinal streaked pattern, parallelling the walls, may also be due to multiple fractures, film-like layers of chlorite, or streaks of tourmaline or sulphides. The latter are generally no more than a few millimeters wide, and are of various lengths up to several meters.

Tourmaline, when present, is generally abundant, and conspicuous because of its black color, but it is entirely lacking from

most of the veins of the region. It occurs as concentrations of needle-like crystals, not only in streaks but also as irregular shaped masses, some of which have solid tourmaline cores and edges made indefinite by the intermingling of the tourmaline needles and quartz.

Sulphides.—The sulphides too are not restricted to streaked zones, but occur also in masses of irregular shape. Pyrite is by far the commonest, and occurs in particles of a wide range of sizes, from dust-like dispersions to cubes more than a centimeter on a side, and rarely in larger masses. Quantitative determinations have shown that its total bulk is less than one per cent of the vein material. Associated with it is chalcopyrite in distinctly subordinate amounts. Galena is rare, but it may be found in small, local concentrations in many of the veins, and is a sign of excellent local values in gold. Much of the gold is below visible size, but visible particles are not uncommon, and large nuggets have been found in the alluvial diggings.

Fracturing.—Although they are entirely absent from many of the veins, carbonates are locally abundant in some, as late fillings in small cross fractures. They are white to pink in color, and qualitative tests show the presence of calcium, magnesium, iron, and manganese. Other cross fractures that appear to have formed near the end of the ore-forming process are filled with quartz, and still others are filled with bright red, cryptocrystalline silica. Fractures that appear to belong to a much later period of stress are abundant, but contain no mineral filling.

Form.—The veins range in size from tiny stringers to huge "reefs" more than two miles long and many yards in thickness, but in general they are from a few tens to a few hundreds of feet in length, and from one to five feet wide. They seem to be ideally lenticular in form, with horizontal and vertical dimensions approximately a hundred times their thickness. Fatter lenses are uncommon, and generally belong to the white bull-quartz variety. As might be expected, most of the lenses have tapering ends, but this is not always true, for some with very blunt ends have been encountered in mine development. Such lenses may be in a

linear series, like boats bow to stern, and the rounded sterns truncate the structure of the enclosing rocks. Numerous other cases have been observed underground of a lack of conformity between the veins and the structure of the enclosing rock, and indicate that the veins were emplaced, at least in part, metasomatically.

ORE FROM THE SAZA MINE.

History.—The Saza Mine is by far the largest in the Lupa Goldfield. Early in 1934, Mr. Nutting, the discoverer of the Saza reefs, sold them to the East African Goldfields Ltd., who undertook a development plan that resulted in about 13,000 feet of underground development and 20,000 feet of diamond drilling, showing a total ore reserve worth approximately one-fifth of the total money expended. The Company failed toward the end of 1937 and was bought by the Soriano interests of Manila, P. I. The New Saza Reefs Ltd., was soon organized, a mill erected, and production commenced at a rate in excess of twelve-hundred ounces of gold per month, the mill recovery exceeding by a gratifying margin the value of the ore calculated from underground sampling.

General.—Most of the ore specimens from the Saza Mine show only quartz and pyrite, but testing with hydrochloric acid reveals the presence also of carbonate in all of them. This occurs both as small grains closely associated with the pyrite, and as fracture fillings that generally cut across any lineation of the pyritized zones at a high angle. These carbonate veinlets are generally less than 2 mm. thick and many are no more than 0.1 mm. thick and would remain unsuspected except for the acid test.

Pyrite.—The pyrite commonly occurs in lines of crystals, and in the specimens containing a relatively high carbonate content, much of the carbonate may occupy the same zones. Coarse pyrite, up to a centimeter or so on a side, has been observed megascopically, but for the most part it ranges in size from about 1.5 mm. down to 0.01 mm. Furthermore, although a complete range of sizes is generally present, the majority of the grains in any one

specimen are of two predominant sizes, commonly 1.0 mm. and 0.1 mm., or 0.5 mm. and 0.05 mm., and it is conspicuous that these two predominant sizes differ from one another by a ratio of about 10 : 1.

Fracturing.—Much of the pyrite shows clear evidence of rupture, the fractures having been filled with quartz and carbonate. Thin sections of this ore show intensive shattering. The largest quartz grains have extreme undulatory extinction and are generally criss-crossed by two sets of fractures that interlace at low angles to one another. Between these larger grains are areas of finer fragments forming intergranular microbreccia zones through which pass major lines of fracture that are not straight, but which follow a more or less common direction. The smaller pyrite crystals, together with some carbonate and quartz, are strung like beads along these major fractures. The larger pyrite crystals, however, do not lie in the fractures, but are enclosed within the confines of the quartz grains of the fracture walls, as if emplaced metasomatically at the expense of the quartz, although also apparently controlled in their deposition by the channelway influence of the fractures. Such rupture and microbrecciation, entailing the production of open spaces, is evidently attributable to the tensional forces that operated at the time of vein formation, as previously shown.[1]

Gold.—Gold occurs in several of the specimens that are devoid of other minerals than quartz, carbonate, pyrite, and wisps of chlorite. Its occurrence, then, appears to be independent of the lower temperature sulphides such as galena and chalcopyrite. It occurs as fillings in fractures in the pyrite, as droplet-like enclosures in the pyrite, and as irregular grains tangential to the pyrite, but most commonly it is found as grains, of the order of 0.05 mm. to 0.005 mm., in clusters of one or two dozen grains in the quartz remote from the sulphides and carbonate, and apparently independent of them. However, such grains may also occur at intervals along the chains of minute pyrite grains and carbonate filling the fractured quartz.

Chalcopyrite.—Compared with material containing only quartz,

pyrite, and carbonates, specimens containing other minerals are rare, and quantitatively of little importance except locally. Next to pyrite, the commonest metallic mineral at Saza is chalcopyrite. It occurs as small grains enclosed in pyrite, in some cases in fair abundance. Considerable chalcopyrite occurs is some specimens as fracture fillings in the broken pyrite, but its commonest mode of occurrence is as a multiude of minute grains, about 0.025 mm., scattered throughout the quartz near to and around the pyrite. Much of the chalcopyrite is closely associated with the carbonate, and is evidently related to it. In fact it is generally true that increase in sulphides other than pyrite is accompanied by an increase in the carbonate content.

Other Sulphides.—Very rarely some sphalerite, generally accompanied by galena, occurs in the specimens relatively rich in chalcopyrite. The sphalerite grains are relatively large, have irregular shapes, and enclose the other metallic minerals. Euhedral pyrite and subhedral galena occur within the sphalerite, and some of the sphalerite is locally crowded with droplet-like blebs of chalcopyrite. Rounded blebs of chalcopyrite together with rounded or cusp-bounded grains of sphalerite have been observed as enclosures in galena. Linear zones of sphalerite and galena have been found to end in galena terminations. The evidence is not compelling, but it suggests that the order of deposition was chalcopyrite—galena—sphalerite, with overlap due to their approximate contemporaneity.

Galena has been observed to mantle pyrite, replace pyrite, and fill fractures in pyrite. The gold in these specimens has not been observed in relation to sphalerite, but it occurs with chalcopyrite in fractures in pyrite, and as grains about 0.02 mm. in diameter scattered through the quartz and accompanied by grains of galena of about the same size. A few of these grains are composite, part gold and part galena, but there is no evidence of any age difference between the two minerals.

An uncommon type of ore consists of quartz with only chalcopyrite and galena, without pyrite, the sulphides occurring as small lunate and cuspate grains with curved boundaries concave

outward as if they were interstitial to the quartz. Where galena is abundant it may be the only sulphide, but such concentrations of galena are uncommon and small, never more than a few handfulls. They are reputed to be rich in gold, but none was found in such galena concentrations, although galena-rich specimens containing other sulphides are extremely rich in gold. Here and there in the galena are small blebs or irregular areas of a white mineral believed to be altaite, but which may be a silver or gold telluride.

Altaite.—This mineral is most abundant in some of the richest ore that consists of medium grained, euhedral to subhedral pyrite, together with chalcopyrite, sphalerite, and abundant galena. Carbonates are also abundant in this material, and quartz amounts to about 75 per cent of it. The telluride occurs as irregular shaped areas within the galena, and as minute grains scattered throughout the quartz, but commonly in close proximity to carbonate and galena. Generally gold occurs close to the telluride and many telluride grains each contain a grain of gold. Some composite grains, no more than 0.05 mm. in diameter, contain in addition to gold and altaite, a soft, gray, isotropic mineral with the etch reactions of argentite, but the smallness of the grains made microchemical confirmation of this identification impossible.

The telluride is lighter and whiter than galena, has a hardness equal to or slightly less than that of galena, and is isotropic. Its etch reactions differ slightly from those commonly given for altaite. First the reaction is uncertain with 1 : 1 HNO_3, but is consistently positive with more concentrated, and negative with more dilute HNO_3. Second, although negative to liquid 1 : 1 HCl, it is strongly positive to the fumes of HCl.

These properties conform to those of altaite, but until the studies that are now in progress on the mineralogy of the tellurides are completed, the etch reactions cannot be absolutely relied upon. Efforts to confirm the identification by microchemical tests were not successful because of the small size of the grains, and the close association with other minerals causing contamination; but good positive tests for tellurium were obtained with CsCl. It is not

impossible that tellurides of gold, or gold and silver, are present, and one composite grain of gold and altaite contained a minute quantity of a pink mineral that might have been rickardite, although this could not be confirmed.

The mode of occurrence of the altaite in the galena, and the gold in the altaite, give the impression that the tellurium was not introduced in the form of either the altaite or the gold telluride molecule, but entered the system in some form, possibly as tellurium ions, such that it was capable of reacting with the galena, but not with the gold. As it replaces the galena it is at least as late as the galena, and probably later. As it surrounds the gold it is possibly later than the gold, although this is obviously not certain.

ORE FROM DANNY MAHER'S MINE.

Before the advent of East African Goldfields Ltd., Danny Maher located a deposit, that is still known by his name, on the south bank of the Lukolongo River about two and a half miles south of the town of Mawoga. Although some high grade material occurred, the deposit was not of workable grade, and the venture failed. At the time of my visit only the dumps and surface outcrops were available to observation.

The vein appears to be in a small mass of sheared and highly chloritic metadiorite, surrounded by granitic rocks of the Lupa Suite on the north and east, and by alaskite on the south and west. The quartz is more glassy than at Saza, the chlorite content of the ore is higher, and the sulphides are more abundant and occur in larger individual masses. But the peculiar features of the ore at Danny Maher's, by which it differs most from the ore at Saza, are (1) the presence of abundant magnetite, (2) the presence of cubanite, and (3) the absence of galena, altaite, and gold.

Cubanite.—Only a trace of cubanite was found, but it occurs as lath-shaped lamellae in the chalcopyrite, and is believed to be an intergrowth. Therefore, its presence indicates that the deposit was formed at a temperature above 400° C., and probably above

450° C., according to G. M. Schwartz.[6] Small enclosures of sphalerite, quartz, and pyrite also occur in some of the coarse masses of chalcopyrite.

Sulphides and Magnetite.—The pyrite is extensively ruptured and the cracks are filled, in most cases by chalcopyrite, but elsewhere by quartz and carbonate. The magnetite, intermixed with considerable carbonate, and small, scattered grains of chalcopyrite, occurs in zones and irregular masses surrounding the ruptured pyrite and cutting into it. In the lower, right portion of Fig. 1 a large embayment of these minerals may be seen cutting

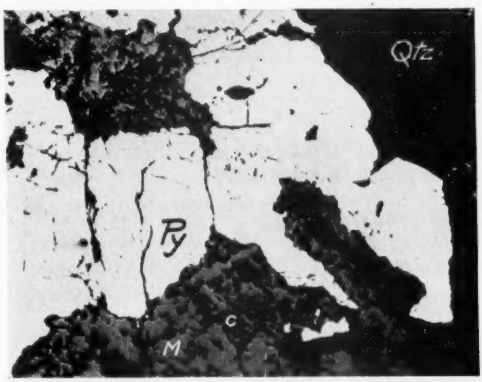

FIG. 1. Ore from Danny Maher's Mine. Pyrite Py (white) embayed by magnetite M (gray) and calcite c (black). × 50.

into a crystal of pyrite. The marginal portion of this embaying mass is higher in magnetite than the core, which is predominantly carbonate. In the upper, left portion of Fig. 1 the magnetite-carbonate mixture can be seen availing itself of the intergranular boundaries between the pyrite grains, and following the fractures in the pyrite. It is believed that these features indicate that the magnetite is later than the pyrite. Some chalcopyrite appears to

[6] Schwartz, G. M. Intergrowths of chalcopyrite and cubanite. ECON. GEOL. *22*: 44–61, 1927.

have preceded the magnetite, since it fills fractures in pyrite that is surrounded by the magnetite; but some of the chalcopyrite, disseminated through the magnetite, was evidently contemporaneous with the magnetite.

Significance of Late Magnetite.—The presence of late magnetite in sulphide ores has recently been called to attention by Schwartz and Ronbeck,[7] but as indicated [8] in a discussion of their paper, the evidence cited by them does not demonstrate that magnetite is later than the sulphides; indeed the evidence given supports the old established idea that magnetite precedes the sulphides. It is, therefore, all the more difficult to explain the late magnetite at the Danny Maher mine.

There is no good evidence of a break in the sequence of ore deposition at Danny Maher's, such as there is at Ak-Tyus, Ehrenfriedersdorf, and the Horne mine, except for the magnetite itself, and the weak evidence that the fracturing of the pyrite and the filling of these fractures by chalcopyrite, apparently preceded the formation of the magnetite. Such evidence does not satisfactorily establish a break in the sequence.

Suggested Explanation.—In a study of the relations between the oxides and sulphides, B. S. Butler makes the following statement: [9] "What controls the formation of these ferrous oxide minerals or sulphides has not been demonstrated, though the concentration of sulphur in some forms in the solutions is doubtless a factor." If it is presumed that the mineralizing solutions at Danny Maher's contained a considerable excess of iron over the amount of sulphur necessary for the formation of pyrite, the following hypothesis seems reasonable. Pyrite would form until nearly all the sulphur was exhausted; the little sulphur remaining would combine with the small amount of copper present, and sufficient iron, to form

[7] Schwartz, G. M. and Ronbeck, A. C. Magnetite in sulphide ores. Econ. Geol. 35: 585–610, 1940.

[8] Gallagher, D. Discussion: Magnetite in sulphide ores. Econ. Geol. 36: 95–100, 1941.

[9] Butler, B. S. Some relations between oxygen minerals and sulphur minerals in ore deposits. Econ. Geol. 22: 237, 1927.

chalcopyrite, and the remainder of the iron would be deposited as iron oxide.

The alternative hypothesis, that the excess iron would crystallize first until the precise amount of iron necessary for the stoichiometric use of the sulphur remained, seems very unlikely. The resulting paragenetic sequence would be the common or "normal" one, but it seems probable that this "normal sequence" is controlled by temperature, rather than by the available amounts of the elements.

Bandy's Sequence.—The hypothesis favored above conforms with the suggestions recently advanced by Bandy.[10] He says,[11]

> . . . after a period of pyrrhotite deposition, either entirely new minerals must form, *i.e.* minerals with new cation elements, or, if iron is still present in the solution it must combine with some other element that is capable of forming minerals of higher cation content than pyrrhotite. It would appear that once iron minerals start to form they continue to form until the iron is completely removed from the mineralizing solutions. Interruptions do not occur in the "normal sequence."

The cation and anion per cents for the minerals at Danny Maher's are as follows:

	Cation.	Anion.
Pyrite	46.6	53.4
Chalcopyrite	65.0	35.0
Magnetite	72.4	27.6

Bandy, of course, makes a clear distinction between the oxide sequence and the subsequent sulphide sequence. But the above sequence conforms to two of his principles, (1) that the anion content progressively decreases in the sulphide sequence, and indeed in the whole sequence, and (2) that the iron deposition, once started, continues until all of the iron is removed from solution. There does not seem to be any theoretical reason why the above sequence should not occur, provided that the mineralizing solution was greatly deficient in sulphur and high in iron.

[10] Bandy, M. C. A theory of mineral sequence in hypogene ore deposits. ECON. GEOL. 35: 359–381; 546–570, 1940.

[11] Bandy, M. C., idem, p. 377.

Magnetite Instead of Hematite.—If the iron oxide had been deposited as hematite it might be looked upon as less abnormal, but its deposition as magnetite seems unusual, particularly because of the general concept that magnetite is a high temperature mineral, which is, of course, not always true.

Kuhara's experiments [12] indicate that the valency of the environment, rather than the temperature, determines whether iron oxide precipitates as magnetite or as hematite. If both the solutions and the precipitants are ferrous, magnetite will form; if either the solutions or the precipitants are ferric, hematite will form. The iron in pyrite, and in chalcopyrite, is ferrous, and so is the iron in chlorite, which is abundant in this deposit. The ferrous nature of the environment may, therefore, account for the deposition of the excess iron as magnetite instead of hematite.

Other Examples.—A feature of the occurrence of late magnetite at Danny Maher's that at once casts doubt upon the hypothesis of origin suggested is the rarity of such occurrences. The Empire mine,[13] Utah, affords an excellent example of late magnetite, and it is also known from the Northpines mine,[14] Ontario, the Rouyn district,[15] Quebec, and the San Carlos Mountains,[16] Mexico. However, all of these are high temperature replacement deposits, either actually pyrometasomatic deposits or closely akin to that type. None are quartz-vein deposits like Danny Maher's; and only in the Empire mine is the magnetite later than chalcopyrite.

Temperature.—Although the temperature of deposition of the magnetite may have been lower than the temperature of deposition of the chalcopyrite, it may yet have been higher than the temperature at which galena could form; and indeed the presence of

[12] Kuhara, M. Experiments on the hydrothermal precipitation of magnetite and hematite. Jap. Jour. Geol. and Geog. 4: 1–32, 1925.

[13] Butler, B. S. Geology and ore deposits of the San Francisco and adjacent districts, Utah. U. S. Geol. Surv., Prof. Paper 80: p. 84, 1913.

[14] Hanson, G. Some Canadian occurrences of pyritic deposits in metamorphic rocks. ECON. GEOL. 15: 594, 1920.

[15] Cooke, H. C., James, W. F., and Mawdsley, J. B. Geology and ore deposits of Rouyn-Harricanaw region, Quebec. Canada Geol. Surv., Mem. 166: 160–161, 1931.

[16] Bastin, E. S. Ore deposits of the San Carlos Mountains. Univ. Mich. Studies, Sci. Ser. 12: 168–169, 1937.

the cubanite indicates that the temperature conditions at Danny Maher's were high. These features suggest that possibly the end-temperature of the mineralization process here accounts for the paucity of gold in this deposit. Conversely, the lower end-temperature at Saza, indicated by the absence of cubanite and magnetite, and the presence of galena, may have offered more favorable conditions for gold deposition. The data are meager, but it may be suggested that the presence of magnetite and the absence of galena in a vein in the Lupa, may prove to be a positive criterion that the vein is not worth working. The matter should be checked in future investigations.

Another feature that further suggests that the temperature conditions at Saza were lower, and consequently more favorable to gold deposition, than at Danny Maher's, is that Maher's vein lies in a small mass of metadiorite and is no more than a few tens of feet from a fairly large mass of alaskite; whereas the Saza veins lie in an unusually large mass of metadiorite and are several hundred feet from any large mass of alaskite, although small dikes of alaskite occur underground in the mine.

ADDITIONAL DATA.

There are small differences in mineralogy from vein to vein throughout the Lupa Goldfield. The ore of the Luika mine, which lies about four miles west-north-west of Saza, resembles the Saza ore but contains molybdenite in addition to the other minerals. Bayldon's Rukwa mine, another dozen miles to the west, contains some large masses of chalcopyrite, and some of his prospects are surprisingly high in silver. No detailed data are available on the ores from the eastern Lupa Goldfield, but the vein opened by Bousfield contains considerable barite gangue, and Ludlam and Fisher opened up some veins that are unusually rich in galena.

Zoning.—The data should be gathered and correlated, preferably by the Tanganyika Department of Lands and Mines, to see if they reveal any zonal arrangement, as this would be an important step toward delineating the most promising areas for prospecting and mining.

SECONDARY PROCESSES.

Surface Data.—Specimens of galena collected within three feet of the surface at Saza, show remnants of galena coated with an alteration zone consisting of a mixture of anglesite, cerussite, and covellite. Some of the covellite is disseminated among the other secondary minerals, but most of it occurs in a narrow septum between the lead oxidation minerals and the galena, as a concentration of needle-like crystals which appear to penetrate into the galena. Fresh chalcopyrite occurs in the quartz, and also as blebs in the galena, together with blebs of sphalerite and minute areas of altaite. The moderately plentiful pyrite is also unaltered, although traces of limonite occur mixed with the other secondary minerals.

The lead of the anglesite and cerussite may have been derived from the galena about which these minerals have formed, but the copper of the covellite was evidently derived elsewhere, and was brought to its present position by the surface waters that effected the oxidation and formation of the secondary minerals.

It is not uncommon in the western Lupa Goldfield to find fresh pyrite, unaccompanied by limonite, in specimens broken from the surface outcrops. In some there is limonite also, but it is generally present in only small amounts, and occurs in the fractures in the quartz, as if introduced, rather than as pseudomorphic masses. Rarely, minute traces of malachite, or of dendritic manganese oxide, may be encountered, but on the whole there is a conspicuous, and surprising, paucity of supergene minerals in the outcrops.

Underground Data.—Underground at Saza there is likewise little evidence of the activity of supergene processes. Occasional traces of manganese oxide and malachite occur well above the first level, and small quantities of limonite may be found in some fractures on the first level, but it is noteworthy that these minerals appear only in the fractures. It will be recalled that the primary ore specimens already described were entirely devoid of oxidation or secondary minerals, and most of these specimens came from the first level, at depths between 120 and 170 feet, although a few came from the second level 150 feet deeper.

Supergene Enrichment.—Gold assay records are available from three shafts. Each of these shafts shows some high values at depths of about 20, 40, and 60 feet, and the surface values corcorespond closely to the average values of the ore shoots beneath. Assays at the same depth, but from opposite walls of each shaft, show wide divergence of values. In plain language, they are spotty. The same degree of spottiness is also characteristic of the assays taken at five-foot intervals along the levels. Consequently it cannot be concluded that these high values at moderately shallow depths are positive evidence of supergene enrichment. It is at least equally probable that they represent rich spots in the primary ore shoots. The presence of small amounts of manganese and chlorine make it possible that some solution and migration of gold could have occurred, but the magnitude of such effects has been far short of important, or even significant, supergene enrichment.

Summation.—Fresh chalcopyrite is abundant throughout the ores, even at the surface, and although no chalcocite has been observed at Saza, a trace has been noted at Danny Maher's as minute films bordering tiny veinlets of carbonate that cut across chalcopyrite. In summary, then, there is a pronounced lack of evidence of supergene activity in these deposits. Two groups of factors need to be evaluated in seeking an explanation for this lack of expectable oxidation and secondary processes: (1) those involving climate, rainfall, water level, topography, and geomorphic history, and (2) those involving the physical and chemical factors of ore, metal, country rock, fracturing, permeability, and groundwater composition.

Group (1) Factors.—Examination of the factors of the first group leads to the conclusion that oxidation and secondary processes should have been active in the Lupa Goldfield. The present climate is two-seasonal with an arid season approximately equal in length to a wet season with about 40 inches of rainfall. There is, in consequence, a considerable fluctuation of the water table during the year.

This is not the place for a detailed presentation of the geomorphic history of the region, but the evidence shows that in the

recent past there have been several land tilts and climatic changes. The present climate was preceded by a period of comparative humidity, and this, in turn, was preceded by semi-arid conditions. Such conditions, which appear to have been favorable to oxidation and secondary processes, persisted over a long time, for the present topographic surface truncates pre-Cambrian abyssal intrusives, that would require a long erosion history to bring them to the surface, and has attained the stage of maturity.

A protective blanket of superposed rocks cannot explain the lack of oxidation. First, there is no trace of a former rock cover, although it is possible that Paleozoic or Karroo sediments or lavas may have blanketed the region. Second, even if their former presence could be demonstrated, the lack of possible weathering before their deposition, or since their removal, would not be accounted for. On the basis of these factors of the first group, oxidation and secondary processes should have been active, but they were not.

Group (2) Factors.—Some factor, or factors, in the second group must account for the observed facts. The ore and metals involved would lend themselves readily to oxidation if they were accessible to the agents of oxidation. Either the agents of oxidation were prevented by some physical factor from access to the metallic minerals, or these agents were peculiarly incapable of effecting oxidation and secondary processes.

Megascopically the vein material appears to be well filled with fractures. However, the microscope reveals that considerable quantities of the sulphides and gold lie isolated in the quartz between the fractures; that is, they are " frozen " in the quartz and are inaccessible to the agents of oxidation. Furthermore, these fractures are not permeable channelways as might be expected, but are to a large extent sealed with carbonates. Although such carbonate fillings would not effectively seal up fractures against the dissolving action of ordinary surface waters, the groundwater of the Lupa Goldfield has a peculiar composition, owing to the highly albitic character of the country rocks. It contains over one-thousand parts per million of sodium carbonate and bi-carbonate, and is therefore highly alkaline. Water of this com-

position would have little efficacy as a solvent for the carbonates of calcium, magnesium, and iron, and fractures filled with these carbonates would remain sealed. Hence, the vein material is far less permeable than its megascopic aspect would suggest.

It may be concluded that the lack of oxidation and secondary processes in the veins of the western Lupa Goldfield is attributable to physical impermeability that is in part maintained by the chemistry of the groundwater.

SUMMARY AND CONCLUSIONS.

The veins of the Lupa Goldfield are hypothermal gold-quartz veins of simple mineralogy. The ore of the Saza mine consists of quartz with carbonate filled fractures, and contains about one per cent of metallic minerals. In decreasing order of abundance, these are, pyrite, chalcopyrite, galena, sphalerite, altaite, and gold. The fracturing of the quartz controlled the entrance of the metallic minerals, and is attributed to tension.

Danny Maher's mine contains pyrite, chalcopyrite with intergrowths of cubanite, indicating high temperatures, and abundant magnetite later than the sulphides. This magnetite is believed to be due to a marked deficiency of the ore forming solutions in sulphur with respect to iron, and was deposited, instead of hematite, because of the ferrous nature of the environment.

There is believed to be a significant relationship between the low end-temperature mineralogy of Saza with its economically successful gold content, and the high end-temperature mineralogy of Danny Maher's with its unpayable gold content. The possibility of zoning is mentioned.

The surprising lack of oxidation and secondary processes in the western Lupa Goldfield is attributed to physical impermeability that is in part made possible by the chemistry of the highly alkaline, sodium carbonate groundwater.

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YALE UNIVERSITY, NEW HAVEN, CONN.,
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ORE MINERALS OF THE LA PLATA MOUNTAINS, COLORADO, COMPARED WITH OTHER TELLURIDE DISTRICTS.[1]

F. W. GALBRAITH.

ABSTRACT.

A recently completed study of about one hundred polished sections of ores from the La Plata Mountains in southwestern Colorado has revealed that certain paragenetic relationships between the sulphides and associated tellurides exist throughout the district. Because of the comparative scarcity of detailed information on the mineralogy of telluride ores it seemed advisable to determine if similar relations exist in other districts where tellurides are abundant. Accordingly, twenty-five sections of ores from Kirkland Lake and Porcupine, Ontario, and twelve sections from Cripple Creek, Colorado, were also examined. Although the number of sections from the latter camps is insufficient to establish the sequence of mineralization definitely for each of these districts as a whole, the relations observed are essentially identical with those exhibited by the La Plata ores.

INTRODUCTION.

THE present investigation is a preliminary attack on the problem of the paragenetic relationships of the tellurides and associated sulphides, and it is the intention of the writer to continue the study of telluride ores from other districts.

The writer is greatly indebted to E. B. Eckel, U. S. Geological Survey, for the opportunity to investigate the La Plata ores, and to Dr. M. N. Short, of the University of Arizona, for guidance and criticism throughout the course of the work. He also wishes to express his thanks to R. D. Hoffman, New York City, who supplied the Cripple Creek specimens; to the managements of the Lake Shore, Wright-Hargreaves, Dome, Macassa, and Toburn mines for samples of their telluride ores, and to C. F. Park, Jr. and A. H. Koschmann of the U. S. Geological Survey for critical reading of the manuscript.

[1] Published with the permission of the Director, U. S. Geological Survey.

THE LA PLATA DISTRICT.

During the years 1935–1937, the geology of the La Plata, Colorado mining district was revised under the direction of Edwin B. Eckel of the United States Geological Survey. Several mines and a great many prospects that had been opened since the earlier survey in 1899 [2] were investigated. It was the writer's privilege to be a member of the Geological Survey party during the first two field seasons, and to aid in the microscopic investigation of the ores, the full results of which will be published in the U. S. Geological Survey report on the district.

The La Plata Mountains, in which the mining district lies, form a southerly outlier of the main San Juan Range. Part of the geology of the district has already been described by Eckel.[3] The mountains consist of a dome-shaped uplift of sedimentary rocks of Paleozoic and Mesozoic age intruded by numerous sills of diorite and monzonite porphyry and by some stock-like bodies of diorite and syenite. The ore bodies generally occur in veins or small replacement bodies in limestone members of the Pennsylvanian Hermosa formation and the Permian Rico formation, in the Upper Jurassic Entrada sandstone, and in limestone and sandstone at and near the base of the Upper Jurassic Morrison formation. They are more rarely associated with porphyry sills or dikes in the Permian Cutler formation. The gangue is predominantly quartz with comparatively small amounts of barite, iron carbonate, and calcite. The vanadium mica, roscoelite, is characteristic of many of the high-grade ores, but is abundant in only one mine. Pyrite, sphalerite, tetrahedrite, galena, and chalcopyrite are, in that order, the most abundant sulphides and are accompanied by hessite, coloradoite, krennerite, calaverite, sylvanite, petzite, and native gold. Gold is by far the most important metallic product in point of value but, owing to the predominance of hessite, is exceeded by silver in weight.

[2] Cross, Whitman: U. S. Geol. Surv., Geol. Atlas, La Plata folio No. 60, 1899 (1901).

[3] Eckel, E. B.: Resurvey of the geology and ore deposits of the La Plata mining district, Colo. Colo. Sci. Soc. Proc., 13: 507–547, 1936.

Minerals.

Pyrite occurs most abundantly as scattered euhedral to subhedral grains in the quartz, where crystal outlines of the cube and pyritohedron can be recognized under the microscope. Although the possession of good crystal form is often considered good evidence of the early formation of the euhedral mineral, it has been clearly recognized that in the presence of a mineral whose tendency to crystallize is strong, such as pyrite, an adjacent mineral will be forced to accommodate itself to the growing crystal faces of its neighbor. The pyrite is veined and embayed by the other sulphides and open spaces in the quartz were filled by them, but no conclusive evidence of replacement either of pyrite by quartz or of quartz by pyrite was observed in the polished sections studied and their mutual relations are therefore in doubt.

A second generation of finely granular to massive pyrite fills tiny vugs in the quartz gangue and in a few places embays euhedral crystals of pyrite.

Sphalerite and chalcopyrite follow pyrite in the sequence of sulphide deposition. These minerals were deposited in open vugs and fissures in the quartz and are also observed as veinlets and embayments in both generations of pyrite, quartz, and carbonate gangue minerals. The chalcopyrite, which is sparingly present, occurs mostly as rounded blebs in the sphalerite, a somewhat doubtful indication of contemporaneous deposition.

Tetrahedrite is an abundant constituent of the ores. In composition the mineral is closer to tetrahedrite than tennantite, although all of the specimens tested microchemically contain an appreciable amount of arsenic. Veinlets and embayments of tetrahedrite in sphalerite and chalcopyrite are a common feature of the ores, and small residual islands of sphalerite occur in tetrahedrite adjacent to larger areas or mainlands of sphalerite.

Galena is widely distributed in the ores but is rarely present in large quantities. It occurs most characteristically as small grains associated with sphalerite, tetrahedrite, and the tellurides. In some of the sections galena has filled open spaces in the gangue,

but more commonly forms irregular embayments, veinlets, and tiny tongue-like projections into adjacent grains of sphalerite and tetrahedrite.

Sulphide Sequence.—Although the general sequence of sulphide deposition is believed to be: (1) pyrite, (2) sphalerite and chalcopyrite, (3) tetrahedrite, (4) galena, as indicated by the evidence described above, it varies in detail from place to place. Thus, in some specimens the later fine-grained generation of pyrite surrounds and embays grains of sphalerite, veinlets of chalcopyrite cut through tetrahedrite, and sphalerite has replaced galena along grain boundaries and cleavage traces (Fig. 1), suggesting a close time relationship between the formation of the different minerals and an overlap in the sequence of deposition.

Tellurides.—Hessite is the most abundant of the tellurides in the La Plata district and is present in most of the ores. Coloradoite, though not as abundant as hessite, is even more widely distributed. Krennerite is much less abundant than coloradoite and is less widely distributed than hessite. Calaverite, sylvanite, petzite, and native tellurium are only sparingly present.

All of the tellurides of the La Plata ores are believed to be of contemporaneous hypogene origin. This conclusion is based upon the fact that in none of the polished sections examined did the telluride minerals exhibit marginal relations toward one another that could be conclusively interpreted as indicating replacement. In one or two sections calaverite and sylvanite form a subgraphic pattern of tiny worm-like inclusions in hessite (Fig. 2) and in another section a similar relation exists between petzite and coloradoite. The interpretation of graphic textures is still highly controversial and their presence is regarded by the writer as inconclusive evidence of either contemporaneity or replacement.

The tellurides occur principally as mutual intergrowths filling open spaces in the gangue and replacing the sulphides, particularly tetrahedrite. This mineral contains veinlets, embayments, and narrow tongue-like projections of the replacing tellurides (Fig. 3) and in many sections is found only as residual grains within the tellurides.

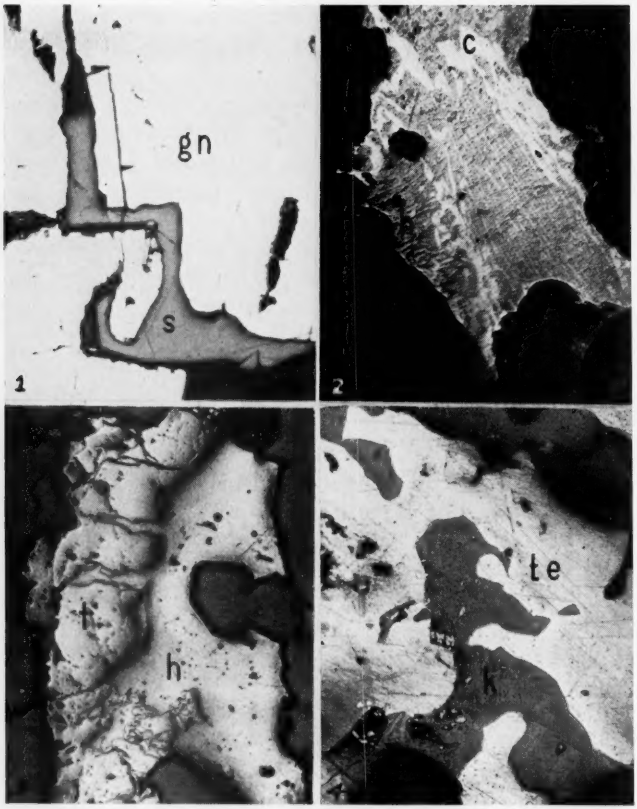

FIG. 1. Sphalerite (s) replacing galena (gn) along cleavages. La Plata district. Gold King mine. ×75.

FIG. 2. Sub-graphic pattern of hessite (h) and calaverite (c). This may indicate rare replacement of hessite by gold tellurides. Gangue is quartz. La Plata district, Gold King mine. ×250.

FIG. 3. Tetrahedrite (t) replaced by hessite (h). Gangue is quartz. La Plata district. Durango Girl mine. ×60.

FIG. 4. Intergrowth of krennerite (k) and native tellurium (te) brought out by etching with concentrated HNO_3. Etch cleavage of krennerite is characteristic. La Plata district, Gold King mine. ×90.

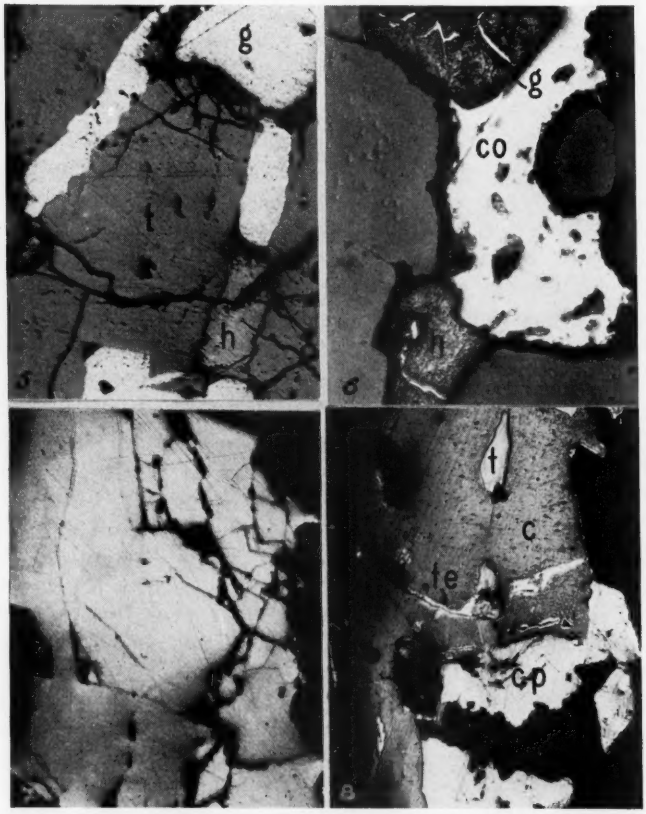

FIG. 5. Native gold (g) and hessite (h) replacing tetrahedrite (t). Gold does not follow fractures in tetrahedrite. La Plata district, Durango Girl mine. × 250.

FIG. 6. Veinlets of supergene gold (g) in hessite (h) etched with 1 : 1 HNO_3. The large area unaffected by the acid is coloradoite (co). La Plata district, Eagle Pass vein. × 157.

FIG. 7. Unidentified gold-silver telluride with cubic cleavage. Cripple Creek, Cresson mine. × 190.

FIG. 8. Veinlets of supergene native tellurium (te) in calaverite (c) which has replaced tetrahedrite (t) and chalcopyrite (cp). Gangue is quartz. Cripple Creek, Vindicator mine. × 190.

Gold.—Native gold is present in appreciable amount in the ores of several properties in the La Plata district. In nearly every occurrence it is intimately associated with the tellurides of gold, silver, and mercury, and is believed to be of hypogene origin. Although much of the gold has filled open spaces in the gangue, the greater part forms a network of tiny veinlets and small irregular masses in tetrahedrite, coloradoite, and hessite (Fig. 5) and exhibits a marked affinity for those minerals in the order named. Although these networks of native gold superficially resemble the delicately interlacing pattern formed by supergene gold in other polished sections examined by the writer, the individual veinlets do not follow fractures in the host, nor do they make off from open cracks that served as channelways for the descending solutions. The gold rarely replaces other minerals. In one section from the Bessie G. mine native gold accompanies cinnabar, which was deposited in vugs lined with very late quartz. This occurrence probably represents the final stage of hypogene mineralization.

Alteration.—Supergene alteration has had little effect on the telluride ores, and supergene minerals are generally present in only small amounts. The most abundant of these is "limonite" which is sparingly present in several polished sections, usually as an alteration product of pyrite or iron carbonate. Both anglesite and cerussite are present in small quantity and replace galena along grain boundaries and cleavage traces. Minute amounts of covellite replace bornite, chalcopyrite, and tetrahedrite along fractures and grain boundaries.

In a section of telluride ore from the Eagle Pass vein, native gold fills tiny fractures and follows minute open cracks along the cleavage traces of hessite (Fig. 6), in distinct contrast to the more common mode of occurrence as described above. This is the only native gold observed in this study that is believed to be of supergene origin.

CRIPPLE CREEK.

The telluride deposits at Cripple Creek[4, 5, 6] are too well known to require more than a brief description. They occur mainly in an irregular mass of latite-phonolite, syenite, tuffs, breccias, basic dikes, and also in adjacent pre-Cambrian rocks. The ores were deposited chiefly in open spaces and large vugs along some of the veins have yielded phenomenally rich ore. The principal ore mineral previously described is calaverite, but more recent studies by Tunell indicate that krennerite is just as important as calaverite.[7] Also present in the ores are other tellurides, pyrite, sphalerite, galena, tetrahedrite, stibnite, and molybdenite. The gangue is largely quartz, fluorite, dolomite, and adularia, but other gangue minerals, including roscoelite and celestite are present.

The specimens of Cripple Creek ores studied by the writer came from the Cresson, Vindicator, and Independence mines. The paragenetic relations observed in the polished sections are almost identical with those described from the La Plata district. Pyrite is fairly abundant and occurs as euhedral to subhedral grains in the quartz. Sphalerite is only sparingly present and is accompanied by chalcopyrite, both of which fill open spaces in the quartz and vein and embay the pyrite. Tetrahedrite is abundant and veinlets of this mineral cut across sphalerite and chalcopyrite. Hessite and calaverite are present in appreciable quantity and extensively replace tetrahedrite as veinlets, narrow tongues, and irregular masses, and small residual grains of tetrahedrite are commonly observed in the tellurides. Veinlets and irregular masses of native gold replace sulphides and tellurides and fill open spaces in the quartz.

One interesting feature of the Cripple Creek ores was the dis-

[4] Cross, Whitman, and Penrose, R. A. F., Jr.: Geology and mining industries of the Cripple Creek district, Colo. U. S. Geol. Surv., 16th Ann. Rept.: 1–209, 1895.

[5] Lindgren, W., and Ransome, F. L.: Geology and gold deposits of the Cripple Creek district, Colo. U. S. Geol. Surv., Prof. Pap. 54, 1906.

[6] Loughlin, G. F., and Koschmann, A. H.: Geology and ore deposits of the Cripple Creek district, Colo. Colo. Sci. Soc. Proc., 13: 219–434, 1932.

[7] Koschmann, A. H.: Personal communication.

covery in a section from the Cresson mine of a gold-silver telluride with the following characteristics:

Color bluish-white against hessite:
Hardness C:
Isotropic:
Perfect cubic cleavage as indicated by two sets of cleavage traces at right angles, but with no triangular pits as in galena.
HNO_3 (1:1)—Does not stain. Perfect parallel etch cleavage appears after drop is washed off.
HCl—Fumes tarnish. Some grains slightly darkened, others negative.
KCN—Negative.
$FeCl_3$—Quickly stains iridescent.
KOH—Negative.
HgCl—Stains light brown.
HNO_3 (conc.)—Stains brownish-bronze, no etch cleavage appears after drop is washed off.

The mineral gives strong microchemical tests for silver with both potassium mercuric thiocyanate and potassium bichromate, indicating a silver content comparable with that of petzite. It also gives strong tests for gold with pyridine-HBr solution and for tellurium with cesium chloride.

These characteristics correspond with those of no known telluride, and this occurrence probably represents a new mineral (Fig. 7).

Another feature of considerable interest is the presence of native tellurium as a supergene alteration product of calaverite, which it cuts along minute fractures (Fig. 8). The native tellurium was identified by means of both etch and microchemical tests. The relation existing between the surface of the ground and the specimen containing native tellurium is not known.

KIRKLAND LAKE AND PORCUPINE, ONTARIO.

The gold ores of Kirkland Lake have been admirably described by Todd,[8] those of Porcupine by Burrows,[9] Graton,[10] and others,

[8] Todd, E. W.: Kirkland Lake gold area. Ont. Dept. Mines, Thirty-seventh Ann. Rept., Part 2, 1928.

[9] Burrows, A. G.: The Porcupine gold area. Ont. Dept. Mines, Thirty-third Ann. Rept., Part 2, 1925.

[10] Graton, L. C., and McKinstry, H. E.: Outstanding features of Hollinger geology. Can. Inst. Min. Eng., 36: 1–20, 1933.

and a number of telluride occurrences in these districts have been described by Thomson.[11]

Both areas lie in narrow east-west synclines along which Timiskamian sediments have been folded into the Keewatin basement. At Porcupine the deposits are found mostly in the Keewatin lavas, although at the Dome mine the Timiskaming is also involved in the ore structures. At Kirkland Lake the ores are largely confined to the graywackes and conglomerates of the Timiskaming, and to porphyry masses that intrude this series. The veins consist of sheared and brecciated rocks partly replaced by quartz, carbonates, sericite, chlorite, etc. Masses of quartz fill openings in the brecciated zones, and native gold, tellurides, and sulphides occur in streaks and minute fractures in the quartz and associated gangue. Pyrite is the principal sulphide, but chalcopyrite, sphalerite, pyrrhotite, and galena occur in smaller quantities. The tellurides include altaite, calaverite, krennerite, coloradoite, and petzite.

In the polished sections studied by the writer, mineral relationships are similar to those observed in the La Plata and Cripple Creek ores. Pyrite, the most abundant sulphide, occurs as euhedral to subhedral grains disseminated through the quartz gangue. Sphalerite and chalcopyrite are present in small quantity. They replace pyrite and the gangue and fill fractures in the gangue. Sections from the Dome mine show the presence of innumerable tiny blebs and small irregular areas of pyrrhotite in the sphalerite.

Although altaite is the most abundant telluride observed in the ores, they also contain appreciable amounts of coloradoite, calaverite, and krennerite. Small quantities of a mineral believed to be hessite are also present, but the grains were too small for positive identification.

The tellurides are believed to be of contemporaneous hypogene origin as no marginal relations indicating replacement of one telluride by another were observed in the sections studied. They fill vugs and fractures in the quartz, vein and embay the sul-

[11] Thomson, Ellis: Contributions to Canadian Mineralogy. Univ. of Toronto Studies, Geol. Ser. Nos. 15–40, 1922–1937.

phides and carbonate gangue minerals. Veinlets of native gold cut sulphides, tellurides, and gangue, and irregular masses of gold were deposited in open spaces in the quartz.

As would be expected in an area recently subjected to intense glacial scour, supergene alteration of the ore minerals is negligible. In the specimens examined it consists entirely of minute areas of native tellurium deposited along tiny open fractures in the tellurides, and similar to the occurrence of native tellurium in the Cripple Creek specimens.

SUMMARY.

The general sequence of hypogene mineralization in the ores of the La Plata Mountains, Cripple Creek, and eastern Ontario exhibit marked similarity. Although the general character of the ores varies in detail, and certain minerals are more abundant in one district than another, the following sequence of mineral formation is believed to be characteristic.

The main stages in the history of ore formation are:

1. Deposition of quartz and pyrite.
2. Carbonates and other minor gangue minerals.
3. Vein sulphides in the following order:
   - *a.* pyrite
   - *b.* sphalerite and chalcopyrite
   - *c.* tetrahedrite
   - *d.* galena.
4. Tellurides; exhibiting no conclusive evidence of replacement and therefore believed to be of contemporaneous age.
5. Native gold.

Supergene alteration of the ores is relatively unimportant, but the occurrence of native tellurium as a supergene replacement product of telluride minerals in ores from both Cripple Creek and Porcupine is, to the writer's knowledge, the first of its kind to be described.

UNIVERSITY OF ARIZONA,
TUCSON, ARIZ.,
Oct. 15, 1940.

TURQUOIS DEPOSITS OF COLORADO.

RICHARD M. PEARL.

ABSTRACT.

Colorado ranks as the second state in the production of turquois, which comes from near the towns of Villagrove, Manassa, Leadville, and Creede.

The deposits occur in weathered acid igneous rocks rich in alkalic feldspar. The turquois is found as veins and nodules in faults, fissures, and cavities. The Hall mine near Villagrove is in felsite porphyry, an Oligocene volcanic flow locally cut by quartz latite. The King mine near Manassa is also in felsite porphyry, probably an extrusive member of the Miocene Santa Fe formation, which is locally cut by felsite, possibly trachyte. The Turquois Chief mine near Leadville is in the Algonkian Silver Plume granite. Turquois is found near Creede in a stream bed, but the source is unknown.

The three lode deposits were formed by circulating meteoric waters that leached and concentrated the constituents of turquois from the surficial rocks and precipitated them from cold solution in fracture and shear zones. The phosphorus was probably derived from apatite; the copper, from copper ores; and the aluminum, from the alteration of feldspar; iron and silica are impurities.

INTRODUCTION.

Colorado is second to Nevada among the states in the mining of turquois, accounting for about 15 per cent of the United States production of about $30,000 in 1938. Well over half of the output of American gems is represented by turquois, and the United States is the most important producing country. Its good quality has made Colorado turquois widely known, although much of the material is sold without indication as to its source.

The first published mention of turquois in Colorado seems to have been in 1870 by Smith,[1] who had in his collection specimens cut in keystone shape, drilled, and formerly worn in a bracelet, which he had obtained from a Ute chief. The stones were sup-

[1] Smith, J. A.: Catalogue of the Principal Minerals of Colorado. Central City, 1870, p. 15.

posed to have come from an uncertain locality in southern Colorado. "They are highly prized by the Indians," he said, "and it is with much difficulty that they can be induced to part with them." Little else has appeared in print concerning Colorado turquois, except brief mentions in *Mineral Resources of the United States.*

Four turquois localities are known in Colorado, near the towns of Villagrove, Manassa, Leadville, and Creede. Reported occurrences near Holy Cross National Monument, Durango, and La Jara have also been investigated but without success.

Field Work and Acknowledgments.—The field work was done in the summer of 1939, and maps were made of the mine properties. The laboratory work, including the making of ten quantitative chemical analyses, was done during the succeeding ten months.

The writer is indebted to Professor R. D. Crawford of the University of Colorado for general supervision and suggestions. He is also indebted to Professors P. G. Worcester, E. E. Wahlstrom, and R. D. George, and to Doctors L. R. Page, and B. K. Stewart. The owners of the properties, Mr. A. J. Hall of Villagrove and Mr. W. P. King of Manassa, made the field work possible by furnishing transportation or lodging. Mr. Fred McNair of Leadville and Mr. Arthur McNair of Boulder loaned original maps and records and arranged the examination of the mine near Leadville. Thanks are due also to Mrs. J. McConnell of Denton, Texas, Mr. Ralph Sherman of Alamosa, Mr. Chester Howard of Denver, and Mr. Ralph Carrington, for transportation and help.

VILLAGROVE DEPOSIT.

The Hall turquois mine is in northeastern Saguache County, 8 miles northwest of Villagrove, in the Cochetopa Hills, at an altitude of about 10,000 feet, and is 5 miles east of the Bonanza mining district.

Although some copper mining was done over fifty years ago at the Hall mine, the turquois was unrecognized and was first

reported by Randall [2] in 1893. A find of turquois nuggets on the surface of the hill above two old shafts sunk by 1903, lead, in 1936, to the digging of a pit, which was the start of the operations that have made the mine the most valuable gem producer in Colorado.

Mining and Marketing.—The active workings of the Hall mine consist of a pit, open cuts, and underground workings. The pit is 102 by 84 feet at the surface, and tapers to a depth of 54 feet. In the spring when water is available, 4 or 5 tons of rock from the dump is hand sorted daily, with a yield of several pounds of turquois. The color of the mineral shows more brightly when wet, and the rock is more friable. The roughly trimmed fragments and water are placed in a cement mixer, which effectively loosens the adhering rock. The turquois is then trimmed with "nippers" and sold uncut for prices ranging from $15 to $45 a pound, according to size, thickness, color, and veining.

Geology.—The turquois occurs as veins and nodules, filling openings in weathered felsite porphyry. The two forms, although of different value because of unequal thickness, are similar in origin; both occupy pre-existing cavities. The veins occupy faults and fissures, whereas the nodules are in cavities and in widenings of the fissures. Many nodules are continuous with veins; others are apparently not associated with them, although the probable origin of the turquois indicates that the cavities were fed through minute channels.

Most of the porphyry is light in color, in vivid contrast to the blue and green of the turquois.

It seems likely that the rock is part of the series of Tertiary (perhaps Oligocene) volcanic formations that cover nearly all the surface of the Bonanza district, which lies in an area of lava flows and associated tuffs and breccias, about 4000 feet thick, unconformably overlying older rocks from pre-Cambrian to Pennsylvanian.[3] The extrusive rocks have been divided into eight mem-

[2] Randall, J. S.: Minerals of Colorado. Georgetown, 1893, app., p. 8.

[3] Burbank, W. S.: Geology and ore deposits of the Bonanza mining district, Colorado. U. S. Geol. Surv. Prof. Pap. 169: 15, 1932.

bers, but correlations among them, and between them and the volcanic sequence of the San Juan Mountains are not definite because of intricate faulting, lack of continuity, scarcity of exposures, and lateral variation of the flows.[4] Similarly, it is not possible to decide to which division should be assigned the turquois-bearing felsite porphyry. The rocks dip to the west, and successively older flows are exposed to sight as one travels eastward from Bonanza, so the felsite porphyry is probably one of the earlier ones. Dips and strikes could not be measured because of the absence of bedding or flowage planes.

Under the microscope the felsite porphyry is seen to consist mainly of an altered groundmass of kaolin that includes tabular phenocrysts of feldspar, some of which show signs of twinning as in the plagioclases, but no determination is possible. Quartz, magnetite, limonite, and some hematite or hydrohematite are present. Small flakes of phlogopite, showing pale yellow to brownish yellow pleochroism, are characteristic, and there is some sericite.

The simultaneous arching, tilting, and faulting of the lava beds in the Bonanza district,[5] accompanied by igneous intrusion and followed by mineralization, is probably similar to the sequence of events in the nearby turquois area. Cutting across the felsite porphyry at the turquois mine, is an exposure of less eroded quartz latite of uncertain age. A thin section shows it to be rather basic although it contains subordinate quartz. Orthoclase and plagioclase, much of the latter zoned, are present in about equal amounts, and there is some microcline. The plagioclase could not be satisfactorily determined. Slightly pleochroic augite is present, and biotite is prominent. Prisms of apatite are common, clusters of them being concentrated in certain parts of the slide. All of the minerals except quartz have been much altered; grains of magnetite are numerous. Kaolin, limonite, and sericite make up the rest of the rock.

Small concentrations of ore minerals have been discovered during the search for turquois, and several narrow veins are exposed

[4] Burbank, W. S.: op. cit., p. 17.
[5] Burbank, W. S.: op. cit., pp. 42–43.

in the tunnels. Dark specular hematite, once supposed by the miners to be a platinum mineral, is present in drusy groups of tabular crystals. Pyrite is disseminated in bands. Both hematite and pyrite were found only at depths lower than those reached by the turquois veins. A somewhat similar condition is that at Mount Chalchihuitl in the Cerrillos Hills deposits of New Mexico, where veins of sulphide minerals lie below the oxide zone in which the turquois occurs, and where lead and zinc have been mined at lower levels than turquois and not far from it laterally.[6] Both types of mineralization apparently have depended upon the same system of fissures for their passage through the rocks.

The felsite porphyry is riddled with pre- and post-mineral fissures and faults. Fault gouge and slickensides are common. Slip surfaces are characterized by an opaque, white, furrowed, enamel-like layer, which has in many places a shiny luster. A single block of rock may show so many directions of movement on its various faces that no particular one seems predominant.

Origin.—Three modes of occurrence have been distinguished by Pogue[7] among the turquois deposits of the world. The Colorado deposits are all representative of the second type—"The turquois occurs in acid igneous rocks rich in alkalic feldspars and considerably altered by weathering or deep-seated alteration, or both." Thus they are like most of the commercially important deposits elsewhere.

The field evidence indicates that the Villagrove turquois was formed by meteoric waters that leached and concentrated the essential constituents from the surficial rocks, and later, through saturation, reprecipitated them in fracture and shear zones. The gradation from kaolin containing copper and phosphorus to semi-turquois and true turquois indicates that some of the turquois may have formed directly from kaolin.

Apatite is the most likely source of most of the phosphorus of the turquois, there being in the area no sedimentary rocks which might have furnished organic phosphorus, although some may

[6] Harrington, E. R.: Chalchihuitl. Eng. and Min. Jour., CXLI: 58, 1940.
[7] Pogue, J. E.: The turquois. Nat. Acad. Sci. Mem. 3, XII, pt. 2: 63, 1915.

have come from plants. The dissemination of copper ores throughout the region and the ubiquitous presence of copper stains point to a simple source of the copper of the turquois. Azurite, chalcopyrite, and copper-bearing pyrite occur near the mine. The derivation of the aluminum in the turquois from the feldspar of the felsite porphyry seems certain. The extensive alteration undergone by all feldspar phenocrysts seen in thin section would furnish the alumina required for the turquois. This alumina would be liberated by kaolinization. Kaolin is abundant and sericite less so. Sericitization perhaps had some influence upon the process of turquois formation in that it is favorable to later kaolinization and hence to the production of alumina.[8] The association of sericite with turquois has suggested to some investigators a hydrothermal origin for certain deposits. Sericitization by hydrothermal solutions at a much earlier date may have occurred and have aided subsequent kaolinization by the action of sulphuric acid from decomposing pyrite, as described by Lindgren[9] in the Cerrillos Hills. Such a prior hydrothermal mineralization may have given rise to the hematite.

Iron, like the copper, is present everywhere, and may have come from primary iron minerals in the country rock or from feldspar, which sometimes contains up to several per cent iron in the alkalic varieties. The silica present probably represents the chalcedony or opal with which turquois is often impregnated, having been derived from feldspar [10] as some of its excess silicic acid.

MANASSA DEPOSIT.

The King turquois mine is 10 miles east of Manassa in Conejos County. It is at an altitude of about 7600 feet, on the side of a low hill in the San Luis Valley. Nearby Pinon and Flat Top Mountains, two of the basalt-capped San Luis Hills, rise 2000 feet or more above the floor of the valley.

[8] Paige, S.: The origin of turquoise in the Burro Mountains, New Mexico. ECON. GEOL., VII: 382–392, 1912.

[9] Lindgren, W. in Lindgren, Graton, L. C., and Gordon, C. H.: The ore deposits of New Mexico. U. S. Geol. Surv. Prof. Pap. 69: 166, 1910.

[10] Jung, H.: Über Türkis. Chemie der Erde, VII: 80, 93, 1932.

The deposit was worked in former times by Indians, whose implements and bones may still be found on the property. Diggings were made at random, up to about 15 feet in depth. Pervine King and his son Charles rediscovered the mine in 1890 but believed it to contain copper, until pieces of turquois attracted the attention of tourists and Indians. Mining was begun in 1909 and has continued at intervals since then.

Mining and Marketing.—The mine consists essentially of an elongated pit 333 feet long, 180 feet wide, and 65 feet deep, the walls of which are burrowed into for turquois rock. The rock is blasted, brought to the surface, broken, and trimmed, the nodules and vein fillings being picked out by hand. The turquois is sorted into six grades according to size, color, and freedom from matrix. Some of it is cut by Indians in Manassa, but most is sold to traders, chiefly in Albuquerque.

Geology.—The turquois occurs as veins and nodules, filling openings in felsite porphyry. The turquois-bearing rock has been called andesite,[11] but its extreme weathering in this area prevents identification. Thin sections show only a trace of fresh material, except clusters of quartz grains. The rest consists largely of a groundmass of kaolin and lesser sericite, altered feldspar phenocrysts, and iron minerals.

Three layers of rock constitute the wall of the pit. They are distinctive in color—a top layer stained black, a brown middle layer stained green, and a vesicular gray bottom layer. They have low parallel northeast dips. Thin sections of the three layers are alike, however, and any differences in original composition between what were apparently successive flows are now obscured.

The felsite porphyry is probably one of the volcanic members of the Santa Fe formation, a series of late Miocene sands, conglomerates, and interbedded lavas and tuffs, which underlie the San Luis Valley.[11a] Unconformably above them lies the Alamosa formation, a late Pliocene or early Pleistocene lacustrine series

[11] Larsen, E. S.: Mineral Resources U. S., pt. 2: 895, 1916.

[11a] Siebenthal, C. E.: Geology and water resources of the San Luis Valley, Colorado. U. S. Geol. Surv. W. S. P. 240: 39, 1910.

of impervious blue clays interstratified with porous sands, which now are the source beds of the many artesian wells of this great basin. Exact correlation with any particular member of the Santa Fe extrusives is not yet possible.

Cutting across the felsite porphyry east of the mine are two exposures of felsite, possibly trachyte. The felsite weathers to a red color, but is gray on broken surfaces, and is hard and brittle in contrast to the friable turquois-bearing rock. Microscopic examination is of interest mainly because of the presence of many small grains of apatite.

Origin.—Like the turquois of the Villagrove mine, this deposit apparently owes its formation to the concentration of the turquois components by circulating ground waters that have leached them from the overlying country rock and precipitated them in previously existing openings.

The phosphorus is probably derived chiefly from apatite in the felsite and perhaps in the felsite porphyry. Copper ores in the region are probably the source of the copper. The greater amount of sericite in the feldspar phenocrysts and the groundmass of the turquois rock here than at the Villagrove mine indicates that an earlier alteration of the feldspar of the felsite porphyry by hydrothermal mineralizing solutions, with the formation of sericite, may have been more important here. An earlier formation of kaolin would thus be made possible when meteoric waters, which were still later to precipitate the turquois, acted upon the altered rock after a period of erosion sufficient to bring the rock within their reach. The kaolin, however, was the immediate source of the alumina.

LEADVILLE DEPOSIT.

The Turquois Chief mine is 7 miles northwest of Leadville in the St. Kevin mining district, Lake County. It is just below the crest of the high ridge that separates Turquoise Lake from the drainage basin to the north.

Indians had apparently been aware of its existence for some time. The first systematic mining was done by two Navajos,

who began work on it in the summer of 1935. During the two succeeding summers they produced about a thousand pounds of rough material which they sent south, where it was fashioned and mounted in silver jewelry by others of the tribe.

Mining and Marketing.—The workings, which are on the side of a low hill, comprise a roughly circular open cut, 100 feet in diameter and 25 feet deep, the discovery shaft, an incline leading beneath it, and another circular hole. The turquois is not now being marketed. Gem fragments were found by the writer at adjacent mines. They were small but good enough to warrant a more thorough investigation of the region.

Geology.—The turquois near Leadville occurs in vein and nodule forms, filling pre-existing openings in white, weathered, medium-grained granite. The rock is presumably the same as that which covers a large portion of the St. Kevin district and the adjoining Sugar Loaf district to the south, where also it is cut by extensive shear zones along which it has been silicified, sericitized, and impregnated with ore minerals, chiefly hypogene silver minerals.[12] Extreme alteration is evident almost everywhere. The granite is pre-Cambrian and has been correlated by Behre [13] with the Algonkian Silver Plume granite of the Georgetown quadrangle.

Origin.—The occurrence of the Leadville turquois differs from that of the mines near Villagrove and Manassa in that the country rock is an intrusive medium-grained granite instead of an extrusive aphanitic volcanic porphyry. Other conditions, however, are similar in all three localities. The Leadville deposit apparently has resulted from the concentration of the constituents of turquois by circulating ground waters that dissolved them from the country rock and precipitated them in an extensively fissured and sheared zone. Apatite is the probable source of the phosphorus; although it was not found with certainty in thin sections of the weathered granite, its former presence in the fresh

[12] Schwartz, G. M. in Sandberg, A. E.: Notes on ore minerals from the Sugar Loaf district, Lake County, Colorado. Proc. Colo. Sci. Soc., XIII, no. 8: 496, 1935.

[13] Behre, C. R. in Sandberg, A. E.: op. cit., p. 496.

rock may be assumed. Commercial copper ores in the region indicate an available source of the small amount of copper needed for the turquois. The aluminum was probably furnished by kaolin derived from feldspar, with the assistance of earlier sericitization.

CREEDE DEPOSIT.

The finding of specimens of blue and green matrix turquois near Creede in Mineral County has been reported to the writer by Miss B. K. Stewart. She picked up small pieces of fairly good quality at several places between the Amethyst and Commodore mines, along the bed of West Willow Creek north of the town. No material was found in place, and the fragments appear to have been washed down from above.

Creede is noted for its silver-lead ores occurring in fissure veins in rhyolite. The volcanic country rock, part of the Tertiary extrusives of the San Juan Mountains, and its shattered condition, particularly on the rich Amethyst vein along West Willow Creek, make the area favorable for the occurrence of turquois. On the other hand, the rarity of copper in Creede ores has been remarked upon by Emmons and Larsen.[14] Only a negligible amount has ever been mined. A few copper minerals are found in the region, however, and under favorable circumstances a sufficient concentration could be made to produce the turquois, which does not require much copper for its formation. The known copper minerals in the district are chalcopyrite, malachite, chrysocolla, chrysoprase, and chalcanthite, and perhaps chalcocite and stephanite. Apatite, a likely source of the phosphorus, is present as a common accessory in most of the types of rock around Creede.

UNIVERSITY OF COLORADO,
BOULDER, COLORADO,
Oct. 15, 1940.

[14] Emmons, W. H. and Larsen, E. S.: Geology and ore deposits of the Creede district, Colorado. U. S. Geol. Surv., Bull. 718, 1923.

DISCUSSION AND COMMUNICATIONS

"BAND," "LAYER," AND SOME KINDRED TERMS.[1]

Sir: I have recently had the task of criticising several manuscripts that dealt with ores and rocks made up of layers, lenses, nodules, and the like; most of these papers were on chromite deposits. Their authors evidently had occasional difficulty in choosing between the terms "band" and "layer," for example; and in functioning as critic I often shared their difficulty and felt the need of clarifying my own views. The following paragraphs embody some thinking aloud on the subject. They make no attempt to trace all the variations in usage, or to cite authorities other than the dictionary; their purpose is merely to inquire what certain words mean or in what sense they may profitably be used. They express individual opinion and have no official authority.

A perfect example of a band, in the strict original sense of the word, is a barrel hoop. Now a "band" of ore is certainly not thought of as like a barrel hoop, nor "banded ore" as being bound about with bands. Banded[2] ore, of course, is layered ore, and the bands are the outcrops of the layers on exposed surfaces that are not parallel to the layers. Whoever first spoke of ores and rocks as "banded" must have meant that they were striped; for "band" had come to mean first a hoop-like stripe and then a stripe on any kind of a surface. "Band" in this sense is a two-dimensional term. It has become common, however, to call a layer a "band," such being the evident meaning of the term in the sentence "the bands dip eastward."

This extension of the term is of course illogical; and it is not

[1] Published by permission of the Director of the Geological Survey, U. S. Department of the Interior.

[2] Ores that are banded by merely superficial stains are exceptional and are readily dealt with as such.

justified by necessity, because terms like "banded ore" can often be used without any distortion of meaning. Common sense permits us to say not only that the surface of a ledge of layered ore is banded but that the ore itself is banded—just as we say that a zebra, not merely its hide, is striped. "Banded," "band," and "banding" may therefore properly be used not only to describe the surficial appearance of layered ores but to distinguish them from ores that are not layered. Only when the inner structure of the ore is being described, or whenever, as in stating strike and dip, the ore body is conceived in three dimensions, would it be reasonable to insist on the use of "layer" and its derivatives.

All this reasoning applies equally, of course, to rocks.

"Lens" is obviously the right name for a body whose lens-like form can be perceived at a glance, but some lenses are so extensive relatively to their thickness that they are not readily distinguished from layers. Most so-called layers, indeed, are extensive lenses —a layer in the strict sense must either be of infinite extent or be cut off like the layers in a cake. The choice between "layer" and "lens" is therefore often arbitrary; "lens" will seem appropriate where a tapering edge is actually in view, "layer" where the band extends throughout the exposure, even though it probably tapers out somewhere and may do so nearby.

The verb "to lens"—or "lense"—does not seem to be in our language. If it were, it might logically be used in a sense parallel to "layered": "lensed" ore would thus mean ore made up of lenses. "Lensing out" is sometimes used to mean "tapering out" or "having a lenticular form," and I have seen "lensing" used to mean something like "occurrence of the ore in lenses arranged stepwise." The verb may ultimately break into the language, but in order to bring that about we should prove that it is needed and agree as to what it shall mean.

"Seam" probably came into geological parlance with the miner's term "coal seam." "Coal seam" is less logical than "coal bed," and "seam" applied to a layer several feet thick strains the imagination because it clashes with the everyday meanings of the word. Perhaps the term had better not be used except where it is truly descriptive.

"Sheeting" and "sheeted" are most useful for describing rocks divided by closely-spaced nearly parallel fissures; and it might, therefore, be as well not to apply the term "sheet" to thin layers of ore and thin sills of intrusive rock. Sheeting may be developed in all sorts of rocks by shearing stresses and in massive rocks by weathering. In volcanic rocks it is commonly produced by stresses due to flow and cooling and generally coincides with primary layering, marked by color banding, when that is present.

Up to this point it has been possible to maintain the conservative position—to ask that the words discussed shall be used in their non-technical sense. It seems necessary to make a strategic retreat from this position with reference to "zone."

"Zone" originally meant "girdle," being thus nearly synonymous with "band" and "belt" in their original meanings. It has a strictly two-dimensional sense in the term "Torrid Zone," but it has never been two-dimensional in geology. It may have entered the literature in such a phrase as "zone of contact metamorphism." A geologist could never have conceived of the zone as merely lying on the surface; he would inevitably think of it as the outcrop of a shell having a substantial and more or less uneven thickness. Why, then, has "metamorphic shell" or some such term not come into general use? My guess is that this has not been due to accident, but that we are reluctant to call so irregular and ill-defined a body by a name that connotes a rather simple form. "Layer" does not present this difficulty.

However, "zone" has filled a need in geological writing, in which it has taken on meanings that are far removed indeed from "girdle." It is now commonly applied not only to a rudely shell-like body, or a remnant of it, but to a body of any form—even to a thick layer or lens—characterized by rocks or ores that have certain genetic features in common. It is oftenest used in such phrases as "fault zone" and "zoning of ore deposits." No one can be blamed for using it thus; but neither should conservative writers be blamed if they try now and then to find more strictly logical terms for the bodies now called zones.

"Streak" is a term that I have drifted into sanctioning, or even suggesting, for a comparatively small flattish body that is

not so well defined as a typical lens or layer. An example would be a roughly tabular mass of dunite containing visibly more chromite than the adjoining rock but having no boundary that one could put a finger on. It must be admitted that all but one of the definitions of "streak" found in the available dictionaries make it a two-dimensional term; the single exception, found only in the Standard, cites the homely phrase "a streak of fat and a streak of lean." The outcrop of such a baconian streak, however, would be a streak in the more usual sense; which leads to the very same inconsistency that has been objected to in the case of "band." But an extenuating circumstance can be pleaded in behalf of the three-dimensional "streak" if it is an expressive name for a thing that has no other name—a plea that could not be made for "band." If "streak," thus loosely applied, fills a need as "zone" has done, some inconsistency may come to be condoned in the one case as it has been in the other. Any confusion that might be caused by speaking of the dip of a streak might be avoided by using some such term as "dip of the plane of the streak."

"Horizon" in the stratigraphic sense can find occasional use in describing extensive layered deposits that were once horizontal —or rather level. A "stratigraphic horizon" is not, strictly speaking, a horizon at all, in either the popular or the astronomical sense, but a level surface, parallel to the geoid.[3] At any rate it is a surface, and a writer should not forget the fact, though a little freedom in the use of the term seems permissible. "Metamorphism of calcareous horizons" is absurd, and "ore-bearing horizon" asks us to conceive a plane as containing or supporting a solid. "Ore horizon," on the other hand, seems inoffensive because of its very lack of concreteness; and even the use of "calcareous horizon" to mean a stratigraphic horizon near which calcareous beds generally occur seems defensible, if it has been explained in the proper place and is used often enough to effect a worth-while saving of words. Such a phrase as "all the ore lies near this horizon" is of course beyond cavil.

[3] The distinction between "level" and "horizontal," familiar to topographers and surveyors, has, curiously, escaped the dictionary-makers.

An ore zone, in the current broad sense, might include layers, lenses, and every other sort of body, and extend along a certain horizon.

"Bleb," which is allied to both "blob" and "bubble," suggests a small irregularly roundish or lenticular body not more than a few inches in diameter, "nodule" a small roundish body of more definite outline. "Orbicular structure" consists of an aggregate of orbs—neither "orbicule" nor "orbicle" is in the dictionaries, though the latter word, homologous with "lenticle," ought to be invented.

As for other terms, such as "pod" and "sack-like," it seems unnecessary to say more than that they should be used only where they are aptly descriptive.

FRANK C. CALKINS.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Sept. 25, 1940.

REVIEWS *

Principles of Economic Geography. By ELLSWORTH HUNTINGTON. Pp. 715; Figs. 1044. John Wiley and Sons, 1940. Price, $4.00.

This book starts with the elements of economic geography and leads to the more complex. It is the second book by the author to appear within a few months. The author states that "it goes back not merely to plants, animals and minerals that provide the basic commodities and give rise to basic industries, but further to the physical conditions of earth, air and water." The air and water seem to be adequate; the mineral part seems a bit out of date and rather undigested. The subjects dealt with are too numerous to detail in a short notice but they appear to embrace most of the materials of the Earth's surface, and the problems of peoples in adapting themselves to their environment and industries. Considerable of the material has appeared in other books by the author. There is a great mass of material collected together and if one doesn't leaf over the pages too rapidly he will find a host of facts, related and unrelated, and much of interest regarding human beings and their environment and industries.

Romance of the National Parks. By HARLEAN JAMES. Pp. 240; many plates. Macmillan Co., 1939. Price, $3.00.

This beautiful volume brings together information about the many national parks of the United States. It deals with the history of the movement that led to their creation, with their scenic beauty and what one should look for when he visits them. It is well illustrated with some stunning photographs.

Earth Sciences. By J HARLEN BRETZ. Pp. 259; Figs. 123. John Wiley and Sons, New York, 1940. Price, $2.25.

This is one volume of *The Sciences,* under the editorship of Gerald Wendt, which includes also volumes on Physics, Chemistry, Astronomy, Biology and The Body Functions. It is meant as a part of a "survey

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

course." It is, of course, an elementary and abridged textbook of physical geology, but it is delightfully written and fascinatingly illustrated with clear halftones and excellent sketches of which many are reversed black and white. It is too abridged for a textbook in elementary geology but should serve as an excellent "survey" text and can be recommended heartily for general reading by anyone who desires a layman's view of geology.

Geology of Coal. By OTTO STUTZER, trans. by ADOLPH C. NOÉ. Pp. 461; Figs. 148. Univ. of Chicago Press, 1940. Price, 5.00.

This is a translation of the 2nd edition of Stutzer's German work "Kohle," by Dr. Adolph Noé, assisted by Dr. Thiessen and by A. Godevon Aesch, a real Germanic product with additions of American nomenclature and knowledge. It relates to the nature of coal, its geological environment, and its recovery, with references of course to German coals. Some of it is good, and much of the good part has been added, some of it is a bit out of date, and much of it is excellent information on German *braunkole*, about which American readers become only mildly interested. Of the various chapters, Chapter II relates to the customary physical and chemical properties; Chapter III to the microscopic examination (American methods); Chapters IV and VI to the origin; Chapter VII, stratigraphy; Chapter VIII, petrography; and Chapter IX to disturbances of coal beds. It contains several good illustrations, mostly of German examples and many of Illinois coals, and good bibliographies, but may have difficulty in competing with another recently published book on coal by E. S. Moore.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Subject Index to Literature of South African Geology and Mineral Resources, 1921–35. A. L. HALL. Pp. 288. Union S. Africa, Dept. Mines, Memoir No. 37. Pretoria, 1939. Price, 7s. 6d. *Annotated index to accompany memoirs 25, 27, and 30 (Bibliographies).*

Hurricane Floods of September, 1938. C. G. PAULSON, B. L. BIGWOOD, A. W. HARRINGTON, O. W. HARTWELL, AND H. B. KINNISON. Pp. 562; pls. 20; figs. 61; tables 27. U. S. Geol. Surv. W. S. P. 867. Washington, 1940. Price, $1.25. *Deals chiefly with river floods along the North Atlantic Coast of the U. S. during the Hurricane of 1938. Also sections on marine erosion by storm waves, rainfall and runoff, and groundwater. Well illustrated with photographs, maps and graphs.*

Risborough-Marlow Area, Frontenac County. C. FAESSLER. Pp. 12; figs. 1; Geol. map in color, scale 1:63,360. Quebec Bur. Mines, Geol. Rept. No. 3. Quebec, 1939. *General geology, and economic geology of gold, silver, and tungsten ores of the area.*

Aerial, Geological, and Geophysical Survey of Northern Australia. Interesting short reports on mining districts of Australia. First listed in this journal, Jan. 1940. The following new reports have been received:

NORTHERN TERRITORY REPORTS.

Nos. 24 and 25. **The Southern Extension of the Pine Creek Gold-Field, Pine Creek District.** A. W. KLEEMAN, J. M. RAYNER, AND P. B. NYE. Pp. 9; Pls. 3. Geol. and Geophys. Rept.

No. 28. **The White Range Gold Field, Eastern Macdonnel Ranges District.** P. S. HOSSFIELD. Pp. 14; maps 4.

WESTERN AUSTRALIA REPORTS.

No. 18. **The Twenty Ounce Mining Centre, Pilbara Gold-Field.** K. J. FINUCANE AND C. J. SULLIVAN. Pp. 3; maps 2.

No. 33. **The Mount Broome Area, West Kimberly District.** K. J. FINUCANE. Pp. 2; maps 2.

Continuity of the Hardyston Formation in the Vicinity of Phillipsburg, New Jersey. J. C. LUDLUM. Pp. 15; figs. 11. New Jersey Dept. Conservation and Development. Trenton, 1940.

Metamorphism in the Lake Wakatipu Region, Western Otago, New Zealand. C. O. HUTTON. Pp. 70; pls. 17; figs. 17; tables 19; maps 3, inc. 2 geol. maps in color, scales 1:126,720 and 1:63,360. New Zealand Geol. Surv., Geol. Memoir No. 5. Wellington, 1940. Price, 6s. *Numerous excellent photographs and diagrams of petrofabrics.*

Annual Report, 1939, Tanganyika Geol. Surv. Pp. 23. Dar Es Salaam, 1940. Price, sh. 1/50.

Talc, Steatite, and Soapstone; Pyrophyllite. H. S. SPENCE. Pp. 140; pls. 8; figs. 4; tables 7. Canada Bur. Mines, No. 803. Ottawa, 1940. Price, 50 cents. *A comprehensive treatise covering geologic occurrence, mining, marketing, uses, and the major deposits of the world with emphasis on those of Canada and the United States. Includes world production figures and many chemical analyses. An excellent reference.*

Quicksilver Deposits of the Bottle Creek District, Humboldt County, Nevada. R. J. ROBERTS. Pp. 29; figs. 1; pls. 5 inc. geol. map and structure sections in color. U. S. Geol. Surv. Bull. 922-A. Prelim. Rept. Washington, 1940. Price, 35 cents.

Quicksilver Deposits of the Mount Diablo District, Contra Costa County, Cal. C. P. Ross. Pp. 23; figs. 2; pls. 3 inc. geol. maps in color. U. S. Geol. Surv. Bull. 922-B. Washington, 1940. Price, 10 cents.

Manganese Deposits in the Little Florida Mts., Luna County, New Mexico. S. G. LASKY. Pp. 18; figs. 8; pls. 3 inc. geol. map in color. U. S. Geol. Surv. Bull. 922-C. Prelim. Rept. Washington, 1940. Price, 25 cents.

Local Overdevelopment of Ground-Water Supplies with Special Reference to Conditions at Grand Island, Nebraska. L. K.

WENZEL. Pp. 48; pls. 6; figs. 6; maps 4. U. S. Geol. Surv. W. S. P. 836–E. Washington, 1940. Price, 30 cents.

The Cumberland Coalfield, The Six-Quarters Seam. Pp. 95; figs. 15; maps 1. Fuel Research Dept., National Coal Resources, No. 49. London, 1940. Price 2s. Exhaustive treatise of single coal seam, inc. physical and chemical properties.

Launay Township, Abitibi County. S. H. Ross. Pp. 21; pls. 1; figs. 3; geol. map in color, scale 1:63,360. Quebec Bur. Mines, Geol. Rept. No. 1. Quebec, 1939. *Deals with general geology of the region and the geology of the gold mines of the area.*

An Attempt at the Correlation of the Ancient Schistose Formations of Peninsular India. L. L. FERMOR. Pp. 102; pls. 3; figs. 1. Memoirs of Geol. Surv. of India, vol. LXX, Pt. 2, No. 2. Calcutta, 1940. Price, 2s. 6d.

Subsurface Geology and Oil and Gas Resources of Osage County, Oklahoma. L. E. KENNEDY, W. E. SHAMBLIN, O. LEATHEROCK, AND N. W. BASS. Pp. 35; 1 map, scale 1″ = ½ mile. U. S. Geol. Surv. Bull. 900–E. Washington, 1940. Price, 40 cents. *Describes area west of Bartlesville, and gives summary of the stratigraphy.*

Lépine Lake Area, Destor Township, Abitibi County. H. M. BANNERMAN. Pp. 22; pls. 4; geol. map in color, scale 1″ = 800 ft. Quebec Bur. Mines, Geol. Rept. No. 3. Quebec, 1940. *General geology with section on gold and asbestos deposits of the area.*

Fortune Lake and Wasa Lake Map-Areas, Dasserat and Beauchastel Townships. G. S. MACKENZIE. Pp. 21; pls. 3; maps 3, inc. 2 geol. maps in color, scale 1″ = 800 ft. Quebec Bur. Mines, Geol. Rept. No. 5. Quebec, 1940. *General, structural, and economic geology of this gold mining area.*

Oil and Gas Map of Illinois. A. H. BELL AND G. V. COHEE. Ill. Geol. Surv. Urbana, 1940. Map of state, 28″ × 42″, scale 1:500,000. *Shows location of all oil fields (both present producers and abandoned areas), pipe lines, and refineries, and indicates ownership of each. Also indicates outcrops of coal measures.*

Geology and Ore Deposits of Northeastern New Mexico. G. T. HARLEY. Pp. 95; pls. 5; figs. 11; geol. map 12″ × 14″, scale 1″ = 16 miles. N. Mex. School of Mines, State Bur. Mines and Mineral Resources, Bull. 15. Socorro, 1940. Price, 60 cents. *Emphasizes economic geology. Takes up the region by counties, excluding Colfax Co.*

Manganese. G. I. WHITLATCH. Pp. 21; tables 3. Tenn. Geol. Surv., Markets Cir. No. 4, 2nd edit. Nashville, 1940. Price, 10 cents. *Excellent short treatise on all phases of manganese plus section on actual and potential production in Tenn. Includes list of principal consumers of manganese in U. S.*

Agricultural Limestone Resources of Cumberland, Effingham, Clay, Richland, and Jasper Counties. R. M. GROGAN AND J. E. LAMAR. Pp. 39; figs. 8; tables 12. Ill. Geol. Surv., Rept. of Investigations, No. 65. Urbana, 1940. *Investigation discloses Omega limestone to be chief potential source of commercial lime in these districts.*

SCIENTIFIC NOTES AND NEWS

W. E. PRATT, a director and member of the executive committee of the Standard Oil Company of New Jersey, gave a series of four lectures on petroleum geology before the departments of geology and petroleum engineering of the University of Kansas, March 17–19. His subjects were "Oil in the Earth," "Where Oil Is," "Who Finds Oil, and How" and "Oil and Human Culture." Mr. Pratt is an alumnus of the University of Kansas and a past president of the A. A. P. G.

C. W. WRIGHT, foreign mineral specialist of the U. S. Bureau of Mines, has left again for South America to investigate South American mineral supplies.

W. G. MCBRIDE, professor of mining engineering at McGill University, is the new president of the Canadian Institute of Mining and Metallurgy.

W. D. JOHNSTON, JR. is expected to return in May to the U. S. Geological Survey in Washington from his trip to Brazil, Venezuela and Colombia.

W. H. SWAYNE is with the Anaconda Copper Mining Company geological department at Butte, Montana.

E. H. CLIFFORD, recently studying the possibilities of increased production of non-ferrous ores in the United Kingdom, has been made president of the British Institute of Mining and Metallurgy.

R. E. WILSON has been appointed examining engineer by the Reconstruction Finance Corporation, in Washington, D. C.

DUNCAN MCCONNELL, formerly of the University of Texas geology department, has been appointed assistant mineral economist in the Bureau of Mines to specialize in building materials of mineral origin.

MATTHEW VAN SICLEN, former consulting engineer for the Turkish government, died in Tucson, Arizona on March 3.

T. E. GILLINGHAM, JR. of Oxford, Pennsylvania, who is studying for the Ph.D. degree at the University of Minnesota, has been awarded the Samuel F. Emmons Memorial Fellowship for 1941–42. He will continue his investigations at the University of Minnesota.

The twenty-second annual meeting of the AMERICAN GEOPHYSICAL UNION will be held in Washington, April 30–May 3, 1941. Scientific sessions will be held in the sections of Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, Tectonophysics, and Hydrology.